MINERALOGICAL CHARACTERISATION AND PETROGRAPHIC ANALYSIS OF FENITES IN THE NORTHERN SIILINJÄRVI ALKALI COMPLEX

Matias Carlsson, 37001
Master's thesis in Geology and Mineralogy
Faculty of Science and Engineering
Åbo Akademi University
Supervisors: Olav Eklund (ÅAU)
and Mikko Savolainen (Yara Suomi Oy)
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Abstract

The 2.6 Ga Siilinjärvi alkali complex is one of the oldest carbonatite-glimmerite deposits in the world and is currently being mined by Yara Suomi Oy in two open mine pits. The older granitic and gneissic bedrock has been metasomatically altered to fenite due to the alkali fluids released during the formation of the carbonatite-glimmerite intrusion. Dioritic and metadiabase dykes intersect the Siilinjärvi alkali complex in a northwestern-southeastern orientation.

The aim of this thesis is to identify the mineral assemblages and microtextures of the known fenite types in Siilinjärvi and to observe local variations between fenite in different parts of the studied area. Field mapping and sample collecting was conducted of the entire northern part of the Siilinjärvi alkali complex. A total of 17 thin sections were examined in this thesis with optical microscopy and micro-XRF in order to characterise the geochemical and petrological variations in the different fenite types. The categorisation of fenites according to their fenitisation grades has been adapted in this thesis. It is used to explain the fenitisation stages during the formation of different fenites with different grades.

The results show that the medium-grade fenite, composed of K-feldspar (microcline or orthoclase) and aegirine-augite, is the most common. High-grade fenites are found near the carbonatite-glimmerite intrusion and consist largely of K-feldspar, perthite and blue amphibole. The low-grade fenites are least affected by the alkali metasomatism and are a mix of fenitic and gneissic minerals and textures.

Microtextures in the medium-grade fenites show albitisation of primary and secondary K-feldspar, signifying that both potassium and sodium have been present in the fenitisation. The two alkalis (potassium and sodium) have also produced two distinct high-grade fenites consisting of either blue amphibole and perthite (Na-fenite) or mantle-textured K-feldspar, aegirine-augite and iron oxides (K-fenite).

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Key words: *Fenite, fenitisation, Siilinjärvi alkali complex, alkaline metasomatism, carbonatite-glimmerite, alkaline feldspar, desilication, µXRF*

1 Introduction

The Siilinjärvi alkali complex is a lenticular carbonatite-glimmerite intrusion located in the municipality of Siilinjärvi, 20 km north of Kuopio in eastern Finland. Today the mining of the carbonatite-glimmerite for extraction of the phosphorus bearing mineral apatite is active under the ownership of Yara Suomi Oy. The mining for apatite takes place in two open pit mines, in the main open pit, Särkijärvi, and in the northern satellite pit called Saarinen.

The core of the 2.6 Ga complex consists of rocks belonging to the carbonatite-glimmerite series. The complex runs in an N-S direction and the main carbonatite-glimmerite intrusion is estimated to be 16 km long and 900 m wide (O'Brien, 2015). The depth of the intrusion has been confirmed to 700 metres. Surrounding the entire intrusion is a fenite aureole, which forks into two branches in the northern part of the complex. The fenite aureole formed due to alkali metasomatism, induced by the intrusion, that fenitised the 2.8 Ga basement gneiss. The fenite is comprised of alkaline feldspar, pyroxene and alkali amphibole. Crosscutting the complex are mafic dykes, which are dioritic to doleritic in composition.

The purpose of this study is to define and characterise the fenite lithology in the northern part of the Siilinjärvi alkali complex. This was done by field mapping and sampling along with thin section and micro-XRF analysis. The different fenites are the result of different grades of fenitisation. The hypothesis is that these differences can be observed as mineralogical and petrographical differences between fenites and are correlated to the fenite's spatial relation with the carbonatite-glimmerite intrusion. It is assumed that the low-grade fenites would be least affected by desilication and high-grade fenites would resemble an igneous syenite. These aforementioned fenite types are observed in other alkaline and carbonatite complexes (Kresten, 1988; LeBas, 2008; Morogan, 1994; Vartiainen & Woolley, 1976).

The approximately 8 km^2-sized study area consists mainly of fenite and basement gneiss with some mafic dykes crosscutting the main lithologies. Some carbonatite-glimmerite series rocks are also present. The main characteristic in the northern part of the complex are the two distinct fenite branches, the western and eastern branch. Within the western fenite branch there are ore-bearing carbonatite-glimmerite rocks, which are the source for the alkaline fluids that have caused the fenitisation of the basement gneiss. The ore-bearing rocks seem to be absent in the eastern branch. The structures in the study area are primarily vertical to subvertical and striking NNW to SSE.

2 Geological outline

2.1 Basement gneiss

The Siilinjärvi carbonatite complex intruded into 2.8 Ga migmatitic basement gneiss, which is a part of the basement gneiss complex of Eastern Finland (Fig. 1). The basement gneiss is geochemically mostly a tonalite-trondhjemite-granodiorite (TTG) migmatitic gneiss along with granitoids classified as granodioritic to quartz-dioritic in composition. The migmatite gneiss is heterogeneous with large areas varying between paleosome-dominated banded gneiss to leucocratic gneisses with migmatitic textures. It is unclear if the migmatite gneiss is of sedimentary or magmatic origin. Preston (1954) suggests that the origin of the migmatite is probably a mix of both super- and supra-crustal rocks. The paleosome consists of biotite, hornblende, plagioclase (oligoclase to andesine) and quartz while the neosome consists of mainly quartz and plagioclase. Alkali feldspar (microcline), if present, exists mostly as an accessory mineral in the migmatite gneisses close to the Siilinjärvi carbonatite complex. Grains of blueish quartz are in abundance in the migmatitic gneisses directly west of the northern Siilinjärvi alkali complex. Only minor mica gneiss bands are reported in the migmatites surrounding the study area (Lukkarinen, 2008).

The granitoids are distinguishable from the migmatite gneisses because of their significantly more homogeneous appearance. The granitoids are mostly banded ortogneisses but the banding differs in intensity. Several gneissic granitoids have been identified in the vicinity of the Siilinjärvi alkali complex. The gneissic granitoids are made up of plagioclase (oligoclase), quartz, biotite and hornblende with K-feldspar as either accessory or main mineral. The granitoids occur together with the migmatite gneisses and are cut by the Paleoproterozoic metadiabase dykes of the area. This, together with age determinations made on a similar tonalitic granitoid in the Maaninka area (10 km west of Siilinjärvi), suggests that these granitoids are of Archean age (Lukkarinen, 2008).

2.2 Carbonatite-glimmerite

The ore rock carbonatite-glimmerite makes up 26% of the entire Siilinjärvi alkali complex. The carbonatite-glimmerite rock series has been divided into four different rock types based on the amount of carbonates in the rock. The majority of the ore body consists of glimmerite and carbonate glimmerite which are composed of up to 10% carbonates and 10-20% carbonates, respectively. With a carbonate amount of 20-50% the rock type is called silicosövite. A modal composition of over 50% carbonate minerals is called sövite (carbonatite). The composition of this intrusive rock can vary locally. This is due to the irregular structural relation between the glimmerite and carbonatite endmembers. The striking contrast between the dark coloured glimmerite and light sövite gives the deposit a striped appearance. It is suggested that the carbonatite intruded as veins into the already emplaced glimmerite (Heilimo et al., 2014).

The main minerals in the carbonatite-glimmerite rock series are tetraferriphlogopite, phlogopite, calcite, apatite and amphibole (mostly richterite). As accessory minerals there are mainly dolomite, zircon, magnetite and sulphides. The ore mineral apatite is mined at two open pit mines Särkijärvi and Saarinen (Appendix A). The apatite is quite evenly distributed in the ore body despite the sometimes chaotic appearance of the intrusion. The apatite concentration can be high in carbonatites. If the amount of apatite is over 25%, the rock is classified as an apatite rock. In these rocks the apatite grains can be tens of centimetres wide. A total of 10% of the ore body consists of apatite alone (O'Brien et al., 2015).

2.3 Metadiabase dykes and the quartz diorite intrusion

The youngest rocks in the Siilinjärvi complex are the Paleoproterozoic metadiabases and the quartz diorite. The metadiabase dykes strike NW-SE through the intrusion and the basement rocks. The dykes are metamorphosed and are therefore called metadiabases. They range from a width of a couple of centimetres to tens of metres. The contact zones to the Archean rocks are sheared and brittle. Their contact zones and relation to each other suggest that there are more than one generation of mafic dykes. This is supported by their different compositions. The main minerals include amphibole, plagioclase and chlorite with accessory epidote, quartz and calcite (Mattsson et al., 2019).

The quartz diorite intrusion is on the western side of the complex. Apophyses of the tonalite are in contact with the carbonatite-glimmerite intrusion. The quartz diorite consists of quartz, andesitic plagioclase, hornblende and biotite (Lukkarinen, 2008).

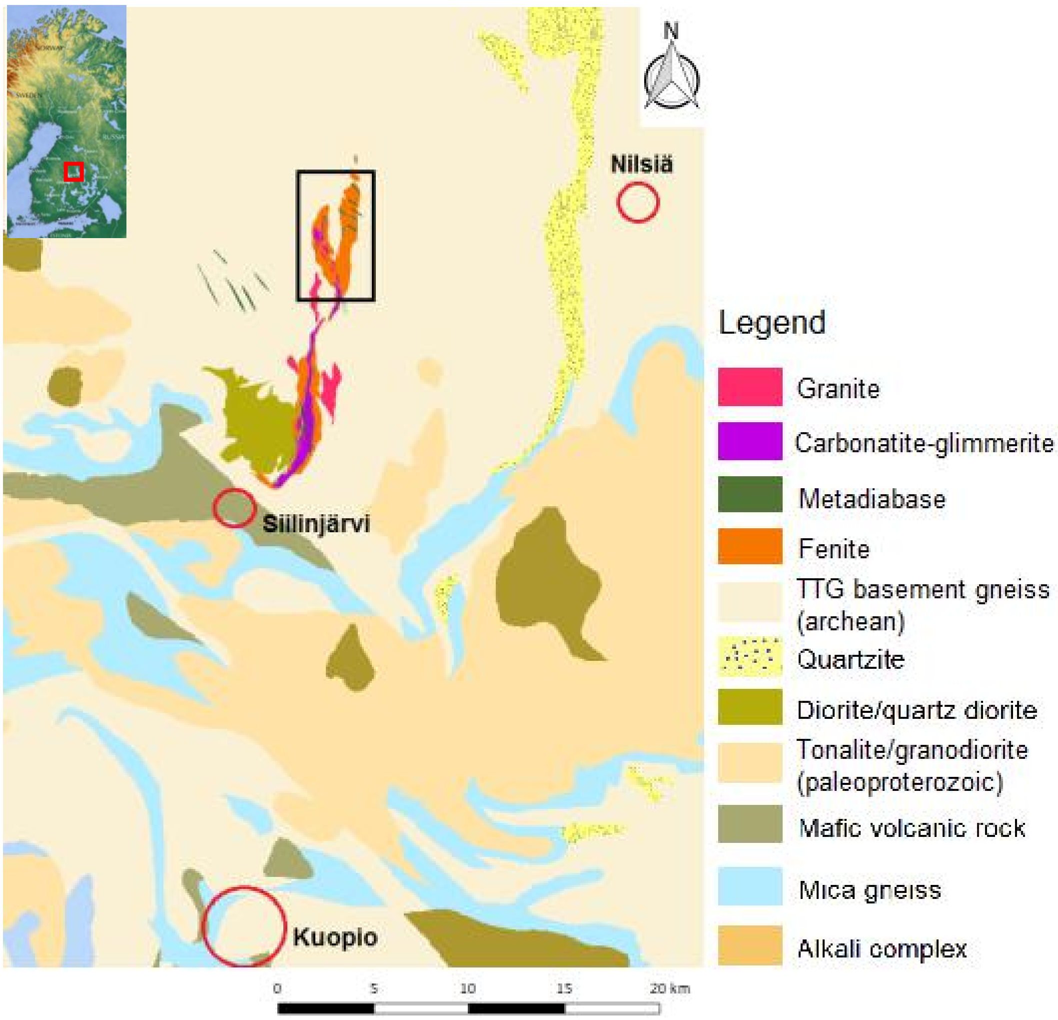


Figure 1. Regional lithological map in 1:1 000 000 scale with the Siilinjärvi alkali complex superimposed in a finer detail. Lithological map from Geological Survey of Finland Hakku database. Mapping area is marked by a black square.

3 Fenite overview

Fenite is a metasomatic rock, which is formed by alkaline to peralkaline fluids that are associated with alkaline and or carbonatitic intrusions. The metasomatic process is called fenitisation and affects the country rock. During fenitisation the fenitising fluids raises the alkaline content of the country rock while also causing desilication. The metasomatic fluid is released in multiple phases from the intrusion. Therefore, the process of fenitisation is polymetasomatic. The fenitising fluids may also have different sources as the intrusive source for the fluids are usually both alkaline and carbonatitic. The alkaline source is often described to be from the melteigite-ijolite alkali rock series (Morogan, 1994).

The fenitising fluid emanating from the intrusion is composed of different elements and volatiles. The elements associated with fenitic fluids are K_2O, Na_2O, CaO FeO, MgO, H_2O and - crucially around carbonatites - CO_2. The ratio between these fluids along with their temperature and pressure is mostly what controls the fenitisation (Elliot et al., 2018). Amphiboles and pyroxenes are susceptible to small variations in the fenitising fluid and therefore their composition can vary (Hogarth & Lapointe, 1984). Two types of fluids affected the basement gneiss in Siilinjärvi. The first type was of low alkali content but high H_2O and CO_2 content. The second type has high alkali content and low CO_2 content and evolved from the first fluid type during the emplacement of the carbonatite (Poutiainen, 1995).

3.1 Fenite mineralogy

The mineralogy varies in fenites because of the infinite combinations of country rock and fenitising fluid compositions coupled with different temperature gradients. A unifying factor to all fenites, though, is the increase of alkalis and alkaline minerals and the removal of quartz within the metasomatically altered rock. The minerals are usually microcline, orthoclase, alkali amphiboles and alkali pyroxenes. Plagioclase with high albite content and perthite is also commonly found in fenites.

The mineralogy is dictated by the protolith only in low to medium-grade fenites. In the most extreme cases of fenitisation the protolith can become a feldspar-rock where it is entirely made up of K-feldspar (Le Bas, 2008).

3.2 Fenite in Siilinjärvi

Surrounding almost the entire carbonatite-glimmerite intrusion is a fenite halo. The fenite is red to pale white in colour and can be found in the carbonatite-glimmerite ore body and even up to 4 km outside of the ore body where the fenite gradually dissipates and turns into the surrounding basement gneiss. The fenite xenoliths within the intrusion can be multiple metres in diameter and are usually surrounded by a mantle of glimmerite. The fenite in Siilinjärvi consists of microcline, alkali amphibole and alkali pyroxene along with accessory minerals such as carbonates, apatite, magnetite, zircon and titanite (O'Brien et al., 2015).

The Siilinjärvi fenite was first discovered in 1864 by A.F. Thoreld. He described it as a syenite which in places included calcite. In 1938, a geological map of the Siilinjärvi area was produced by W.W. Wilkman. Here the outlines of the fenite (then syenite) were much more precise and almost the entire extent of the fenite was mapped. No carbonatite or glimmerite was observed at that time. The discovery of the ore intrusion was made in 1950 after which the studies made in the area multiplied (Puustinen, 2018).

Puustinen (1971) made the first comprehensive study of the complex. At this time, fenite and fenitisation was known to take place around alkalic and carbonatitic intrusions. Despite this Puustinen (1971) describes most of the wall rock as syenite and theorises that a fenite halo of a couple of metres thin may exist around the intrusion. The syenite was categorised to different types based on the dominant minerals found in each type e.g. quartz-aegirine syenite, carbonate syenite and amphibole syenite. This categorisation is still in use today. The only fenite features explained are the ones that are noticeable in areas with the basement gneiss and syenite (Puustinen, 1971).

3.3 Terminology of the Siilinjärvi fenite

The turning point in the nomenclature from syenite to fenite was made by Härmälä (1981). He argued that the previously presumed syenite was actually fenite which he called “syenitic fenite”. The fenite described by Puustinen was named “gneissic fenite” since it displayed gneissic textures and was in the vicinity of the basement gneiss. From here on, the term syenitic fenite or fenitic syenite was used for the enigmatic alkalic rock type in the Siilinjärvi alkali complex and the immediate area. At this time, many metasomatically altered gneisses around the northern parts of the Siilinjärvi alkali complex have been described to be similar to the syenitic fenites found in the complex (Paavola, 1984; 1988).

Lukkarinen (2008) also adopted the term syenitic fenite because of the plutonic appearance of the alkali rock. The term was also used since there was insufficient evidence for the genesis of the syenitic fenite. Lukkarinen (2008) theorised that the syenite was emplaced before the carbonatite-glimmerite rocks. The fenitising fluids, which emanated from the carbonatite-glimmerite, then fenitised the already emplaced syenite.

The latest terminology in use for the pale gray to red alkali rock is fenite (O’Brien et al., 2015). The lack of a distinct sharp contact between the basement gneiss and the alkali rock minimises the possibility of the alkali rock being of plutonic origin. Fluid inclusions in zircon and apatite within the carbonatite-glimmerite have compositions that are fenitic in character (Poutiainen, 1995). These fluids are thought to have produced the fenite halo during the ascent of the carbonatite-glimmerite intrusion (O’Brien et al., 2015).

3.4 Fenitisation stages of a granitoid protolith

Multiple reactions take place within the fenitisation process resulting in many different and sometimes complex mineral parageneses and alteration textures. The migmatitic basement gneiss surrounds the entire northern part of the Siilinjärvi complex and is therefore assumed to be the only fenitised rock type. The relatively homogeneous mineralogy of quartz, plagioclase, biotite and K-feldspar has been fenitised through multiple stages of alkali metasomatism related to the carbonatite-glimmerite intrusion. These stages have been recorded at other localities where fenitisation has affected a granitoid protolith (e.g. Viladkar, 1986; Kresten & Morogan, 1986; Le Bas, 2008).

The first stage of fenitisation of a granitoid is the turbidisation of the alkaline feldspars, primarily the plagioclase. Undulatory extinction and granulation of the quartz is also evident before it is consumed by other mineral phases in the later stages of fenitisation. Biotite breaks down rapidly and is replaced by microline and/or orthoclase and Fe-oxides. Along the veinlets, of which the fenitising fluids are transported, pyroxene and amphibole (e.g. richterite or arfvedsonite) start to form (Vartiainen & Woolley, 1976; Viladkar, 1986).

Further fenitisation causes the breakdown of quartz which leads to rapid growth and formation of green pyroxene and/or blue amphibole between quartz and alkaline feldspar grain boundaries. Blue amphibole also pseudomorphs biotite, which results in biotite being consumed. Albitised margins form around primary K-feldspars and the plagioclase can be completely indistinguishable due to the turbidisation.

The development of alkali pyroxene, usually aegirine, continues and quartz is completely consumed. The albitised corona texture around K-feldspars increases and perthite and chessboard albite can form. The K-feldspars formed by the breakdown of biotite can also inherit the corona texture. Perthite usually replaces the primary alkaline feldspar during high-grade fenitisation. Veins of carbonate can be abundant at this stage but can also be absent. New corona textures can form around the mafic minerals where amphibole replaces pyroxene or vice versa (Vartiainen & Woolley, 1976).

The final stage of fenitisation is where no primary minerals are present and the replacement textures are replaced by recrystallisation textures. After the aforementioned stages, the primary alkaline feldspar has either been replaced by K-feldspar, perthite or albite (Le Bas, 2008). The main mafic minerals are pyroxene or amphibole. At this stage the Na/K ratio of the fenitising fluid can be assumed (see Table 1). In a sodic fenite Na-amphibole and albitic feldspar are dominant but in a potassic fenite the mineral assemblage is mostly K-feldspar (up to 90%), pyroxene and phlogopite. The accessory minerals that have formed at this stage are titanite, apatite and secondary biotite (e.g. Morogan & Woolley, 1988).

A further higher-grade fenite can be present in the contact to the carbonatite or alkali intrusion. It is the highest grade of fenitisation and occurs only in extreme cases where minerals such as nepheline, cancrinite ($Ca_2Na_6Al_6O_6(CO_3)_2 \cdot 2H_2O$), wollastonite, melanite ($Ca_3Fe^{3+}_2(SiO_4)_3$) and phlogopite can be abundant (Sindern & Kramm, 2000; Skelton et al., 2007).

Table 1. The mineralogy during different stages of fenitisation starting from a granitoid protolith and ending in high-grade fenite

Granitoid mineral paragenesis	**K-feldspar**	**Plagioclase**	**Quartz**	**Biotite**
	Albitisation/ turbidisation	Turbidisation	Undulatory extinction	Replaced by K-feldspar and Fe- and Ti-oxides
	Albitisation and formation of perthite	Replaced by K-feldspar	Replaced by pyroxene and amphibole	Rest of the biotite altered into amphibole
Fenite mineral paragenesis	**Albite/perthite**	**K-feldspar**	**Pyroxene and/or amphibole**	
Fenite mineralogy (determined by Na/K ratio of the fenitising fluid)	**Na-fenite**		**K-fenite**	
	Albite/perthite	Amphibole	Pyroxene	K-feldspar
Minerals present only at the highest fenite grade	Nepheline, garnet, wollastonite and phlogopite			

Increasing grade of fenitisation

3.5 Categorisation of fenites

There are countless of different fenite types (Heinrich, 1985). Therefore, it is important to classify them under one method of nomenclature. Multiple authors have proposed many ways to categorise different varieties of fenites. The seemingly simplest way to classify fenites is the source of the metasomatic fluid. It is difficult to distinguish between a carbonatitic and alkaline (ijolitic) magmatic source for fenitisation, since these two usually occur together in the same complex as in Fen, Norway (Kresten, 1988). In the onset of fenite research the nomenclature was joined with the terminology of plutonic rocks. This is because of the fenites' similar composition to syenite.

Another type of frequently used classification for fenites is to separate them into sodic and potassic fenites, with an intermediate type between them. This is done by calculating the ratio of K and Na, which is one of the most important parameters of defining fenites (Elliot et al., 2018). That is why this type of categorisation is widely used. Potassium-dominant fenitisation is characterised by an abundance of K-feldspar along with some phlogopite, pyroxenes and Fe-oxides. Sodium fenitisation leads to a more complex fenite composed of alkaline feldspar, albite, Na-amphibole and Na-pyroxene.

Finally, the third way to categorise fenites is by their physical relation to the source intrusion, i.e. aureole fenites, contact fenites and vein fenites (Kresten, 1988). This type of categorisation is usually combined with a nomenclature which reflects the grade or intensity of fenitisation (Fig. 2). This classification method is most effectively done by Morogan (1994) who subcategorises the aureole fenites into low-, medium- and high-grade fenites. Fenitisation intensity is the most descriptive way to categorise fenites since it takes into consideration the mineralogy, texture and structure.

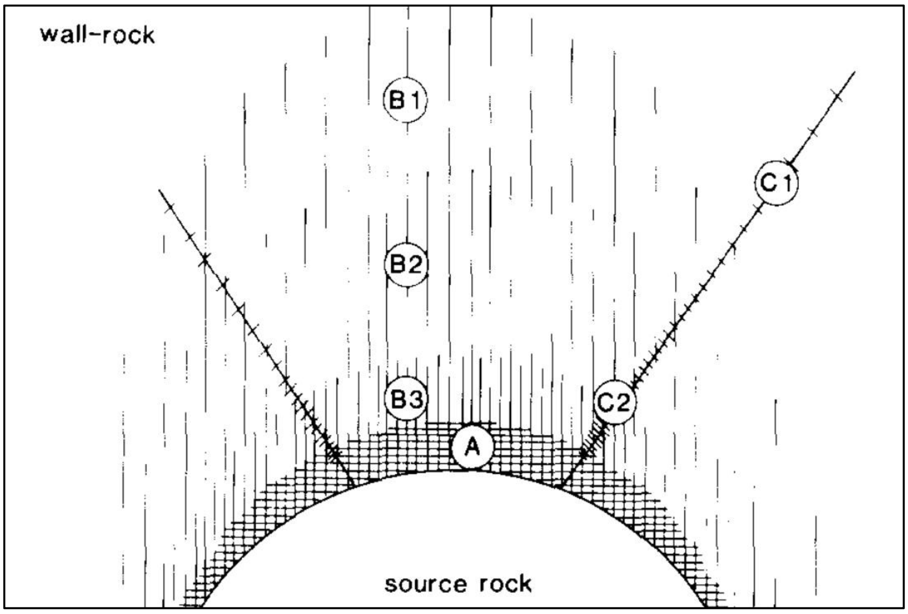


Figure 2. Categorisation of fenites into contact fenites (A) aureole fenites (B1-3) separated into high-grade (B3) medium-grade (B2) and low-grade fenites (B1). Vein fenites (C) are separated into vein fenites within the aureole (C2), that can cause superimposed fenitisation of the pre-existing fenites, and vein fenite outside of the aureole (C1) (Kresten, 1988). In Siilinjärvi the source rock is carbonatite-glimmerite and the wall rock is migmatitic basement gneiss.

3.5.1 Fenitisation grade

The adopted nomenclature used in this thesis is the one used by Morogan (1994). That is because of its flexibility and versatility to be used in any fenite regardless of the mineralogy of the fenite or the protolith.

By definition the low-grade fenites are dominated by textures present in the protolith but with a more fenitic mineralogy. Most of the primary minerals are slightly altered by the fenitisation but some minerals such as quartz can remain unaltered. Low-grade alteration to fenite can be detected both macro- and microscopically. In medium-grade fenites the fenite mineralogy dominates, i.e. fenites enriched in alkalis and depleted in silica. Some relict textures and primary minerals are present. In high-grade fenites all primary textures and minerals of the protolith are absent. The rock is completely alkali metasomatised and all minerals have recrystallised to fenite minerals. High-grade fenites may be misconstrued to be syenites because of their highly igneous appearance (Morogan, 1994).

In areas with low- to medium-grade fenitisation it is essential to understand the protolith for the fenite. Relict minerals and textures belonging to the protolith, in Siilinjärvi the migmatitic basement gneiss, may be misconstrued as products of the alkali metasomatism. This will lead to inaccurate analysis of the fenitisation process, and not least to inaccurate interpretations of the fenitisation grade. The analysis of the fenites rests partially on the assumption that the metasomatically affected basement gneiss was homogeneous. This is because of the difficulty to accurately trace back to the exact mineralogy of the protolith, since many parameters other than the protolith's mineralogy affect the characteristics of a fenite (Elliot et al., 2018).

Beyond the fenite aureole in Siilinjärvi, the migmatitic basement gneiss can indeed be called homogeneous with a few notable exceptions such as wide hornblende and mica schist areas (Puustinen, 2008).

4 Material and methodology

4.1 Field mapping and sampling

Mapping and sample collecting was conducted during the summer months of 2018 in an area that covered approximately 8 km^2. The main focus was on the fenite lithology and its contact relations to the carbonatite-glimmerite intrusion and basement gneiss in the northern area of the Siilinjärvi alkaline complex.

Mapping areas were planned beforehand with the help of bedrock maps and additional mapping information provided by Yara Suomi Oy. To further plan the mapping, digital elevation maps (DEM) with hill shade were created on the open-source geographical information system QGIS (Appendix B). The elevation data was acquired from the open-source provider National Land Survey of Finland (NLS). This was combined with outcrop data gathered during 1978-1980 by the Geological Survey of Finland (GTK) to aid finding areas with outcrops.

Across the entire northern part of the Siilinjärvi alkali complex a total of 244 outcrop observations were made (Fig. 3). Observation data gathered at outcrops was recorded in the Kapalo mobile application developed by GTK. The geological observations are recorded in the WGS84 coordinate system. Every observation has a unique observation ID created by the Kapalo application. Outcrop photographs were linked to the IDs, as well as tectonic measurements. A previous bedrock map combined with the DEM map was created on QGIS and transferred over as a GeoTIFF file to the Kapalo application. The Kapalo observation database was then imported to QGIS where it was further processed to create a comprehensive point file.

Within the fenite lithology, the outcrops at high elevations were often observed to be fenite or diabase. On low elevations the outcrops were usually fenite or glimmerite on the western branch and only fenite on the eastern branch. This was applied later during field mapping when the DEM could be used more effectively in light of this information.

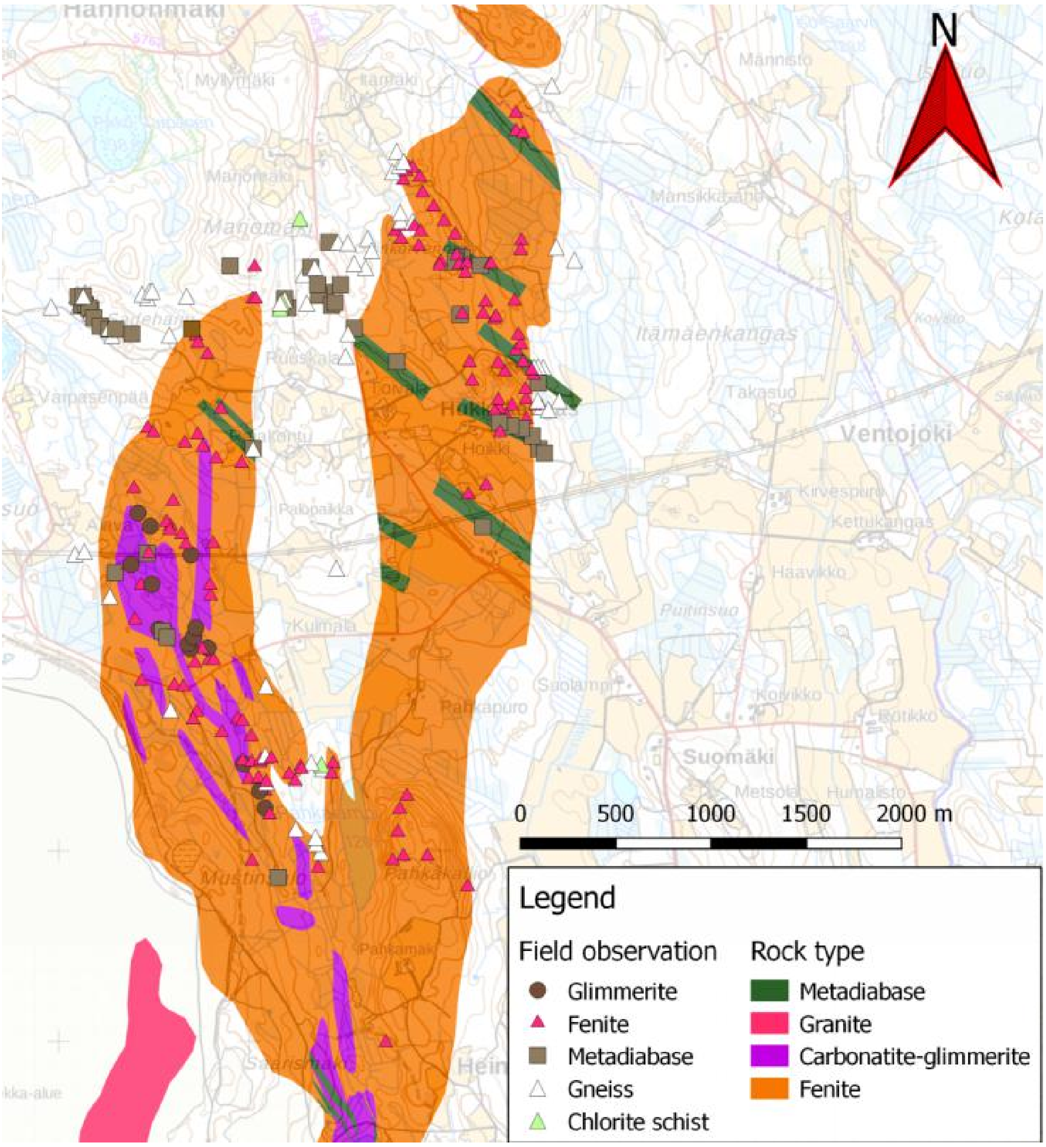


Figure 3. Northern part of the Siilinjärvi alkali complex, including every field observation.

4.2 Micro-XRF

Micro X-Ray Fluorescence (µXRF) is used to detect quantities of different chemical elements and generate a colour map which indicates where the analysed element is. In this study the µXRF used was an M4 TORNADO and the Brauer software. The µXRF is a useful method for analysing larger areas of a sample. Samples that are chosen for µXRF analysis display a complex mineral assemblage or have minerals which are observed in petrographical microscope to be altered. The fenitising fluids, which alter the minerals, are identifiable by analysing a mineral that exhibits zoning or more complex alteration. Therefore, a map that displays the distribution of an element which is mobile and abundant in the fenitisation process, is an effective way to analyse a fenite of any fenitisation grade. Both major and trace element analysis can be conducted on µXRF. In fenites the most important elements to analyse are K, Na, Si, Ba and Sr. These are the most mobile elements and are parameters that can indicate different grades of fenitisation (Elliot et al., 2018; references therein).

4.3 Thin sections

Thin sections of 17 samples were prepared by the author at the thin section preparation facilities shared by Åbo Akademi University and Turun Yliopisto. The thin sections are prepared from 15 fenite samples and one glimmerite and one gneiss sample. Thin sections were prepared from samples which represented different areas of the fenite and had differing appearances on the outcrops. Clear textural differences between fenites on outcrop scale was also an important factor in selecting the correct samples for thin section preparation.

The polished thin sections are 30 µm thick and are glued on a glass slide varying between 1508-1544 µm in thickness. The glue used is a 1:4 ratio epoxy blend of hardener and epoxy glue**.** The polished thin sections are used to distinguish different mineral facies and micro-textures. Primarily they are used to find indicator minerals that can be connected to different grades of fenitisation.

5 Results

5.1 Field mapping

Out of the 244 observed outcrops 126 are fenite, 60 are gneiss, 44 are metadiabase, 14 are glimmerite and five are chlorite schist (Appendix C). Four outcrops contain two or more of the aforementioned rock types. The lithological map provided by Yara Suomi Oy correlated well with the observations made in the field.

5.1.1 Main fenite type

The main fenite type is instantly recognisable in the field compared to the basement gneiss. It is red, pale red to dark green in colour with an unaltered igneous texture. It contains red alkaline feldspar, dark green pyroxene and at times magnetite, amphibole and quartz. This mineralogy is common throughout the fenite lithology in the study area. Both the quartz and the magnetite appear sporadically either as an accessory mineral in the matrix or as veins. Calcite can also be present in the fenite but only in trace amounts. Textures vary dramatically from igneous unaltered appearance to banded appearance. The grain sizes vary from small to pegmatitic and the mineral composition of an outcrop can vary from 90% alkaline feldspar to 90% pyroxene and everything in between. Usually the coarse-grained to pegmatitic parts are composed of sub- to euhedral pyroxenes and quartz or pyroxene and alkaline feldspar (Fig. 4a). Rarely do all three minerals occur together in a pegmatitic fenite. If alkaline feldspar is present, it can be perthitic and/or exhibit a mantle texture with a different coloured rim respective to the core of the mineral (Fig. 4b).

The pyroxene is observed to behave plastically in the fenite in contrast to the alkaline feldspar which appears unaltered. The pyroxenes form coarse-grained aggregates which are at places plastically folded in an otherwise igneous-looking rock with an alkaline feldspar ground mass (Fig. 4c). Pyroxene and alkaline feldspar can form dyke-like aggregates seemingly crosscutting the existing fenite. This occurs almost exclusively on the eastern branch. The dykes are usually over ten centimetres wide and can be followed through an outcrop up to tens of metres. The minerals are no smaller than coarse-grained with the pyroxenes oriented perpendicularly to the direction of the dyke. Along the edges of the dykes the perpendicular pyroxene growth is increased. This is distinguishable especially in the feldspar-rich dykes (Fig. 4e).

Magnetite can behave in a similar way forming coarse-grained aggregates (Fig. 4d). These are uncommon and have most notably been found in areas with cracks and veins filled with abundant magnetite and quartz-magnetite. Amphibole-filled cracks occur scarcely and have been subjected to shearing since the amphibole crystals are elongated and close to fibrous. These cracks are no more than a centimetre thick.

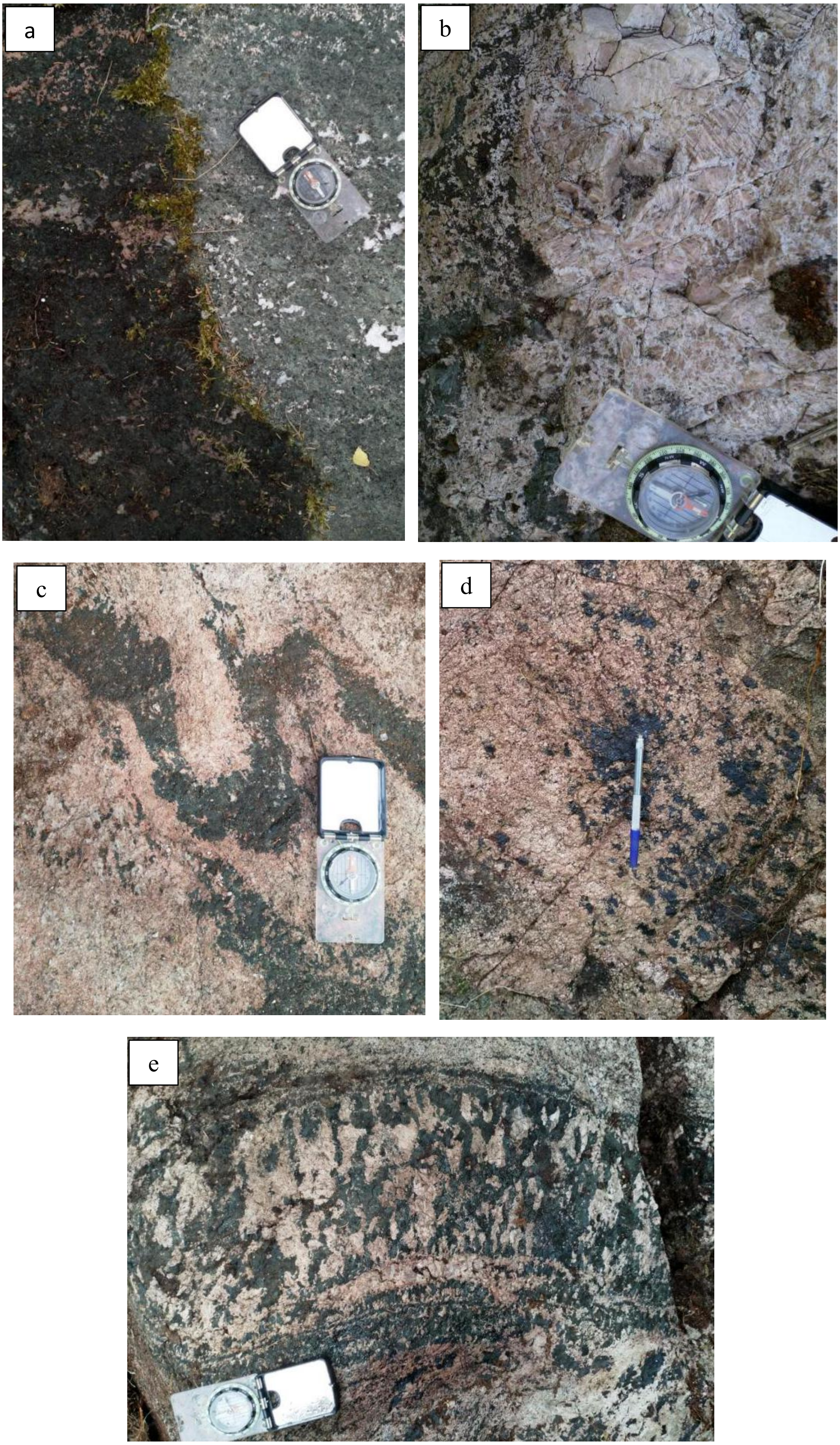

a
b
c
d
e

Figure 4. a) Pyroxene-rich portion with quartz. The left side of the picture is darker because that part of the outcrop is damp. SIKA-2018-56. b) Perthitic feldspar with the smaller grains exhibiting a mantle texture. SIKA-2018-78 c) Aggregates of pyroxenes, which display plasticity. SIKA-2018-23. d) Coarse metallic blue magnetite grains, demonstrated by the magnet-tipped pen. SIKA-2018-92. e) A fenite dyke cross-cutting pre-existing fenite, displaying the perpendicular pyroxene growth especially on the edges of the dyke. SIKA-2018-22.

5.1.2 Fenite gneiss

The contact areas between the fenite and the gneiss are gradual. The fenitisation grade in these areas is generally low and unfenitised basement gneiss can be present very close to fenite gneiss. The gneissic fenite is characterised by the abundant amount of quartz and lack of pyroxenes. Bands of biotite and other gneissic textures quickly disappear at the faint but wide transition zone between the gneiss and the fenite. Despite this, gneissic banding with fenitic composition is observed at multiple locations (Fig. 5a). Veins consisting of alkaline feldspar, pyroxene and quartz are also common on the outskirts of the fenite but not limited to this area. These veins are usually coarse-grained and at times pegmatitic (Fig. 5b). Magnetite grains are uncommon and occur on the eastern edge of the northern alkaline complex. These characteristics of a fenite gneiss can be present on a single outcrop as demonstrated on outcrop SIKA-2018-41 (Fig. 5c). Outside of the fenite aureole, the basement gneiss is unaltered with the exception of a few veins with a fenitic composition, epidote or magnetite filled cracks and blue opalescent quartz.

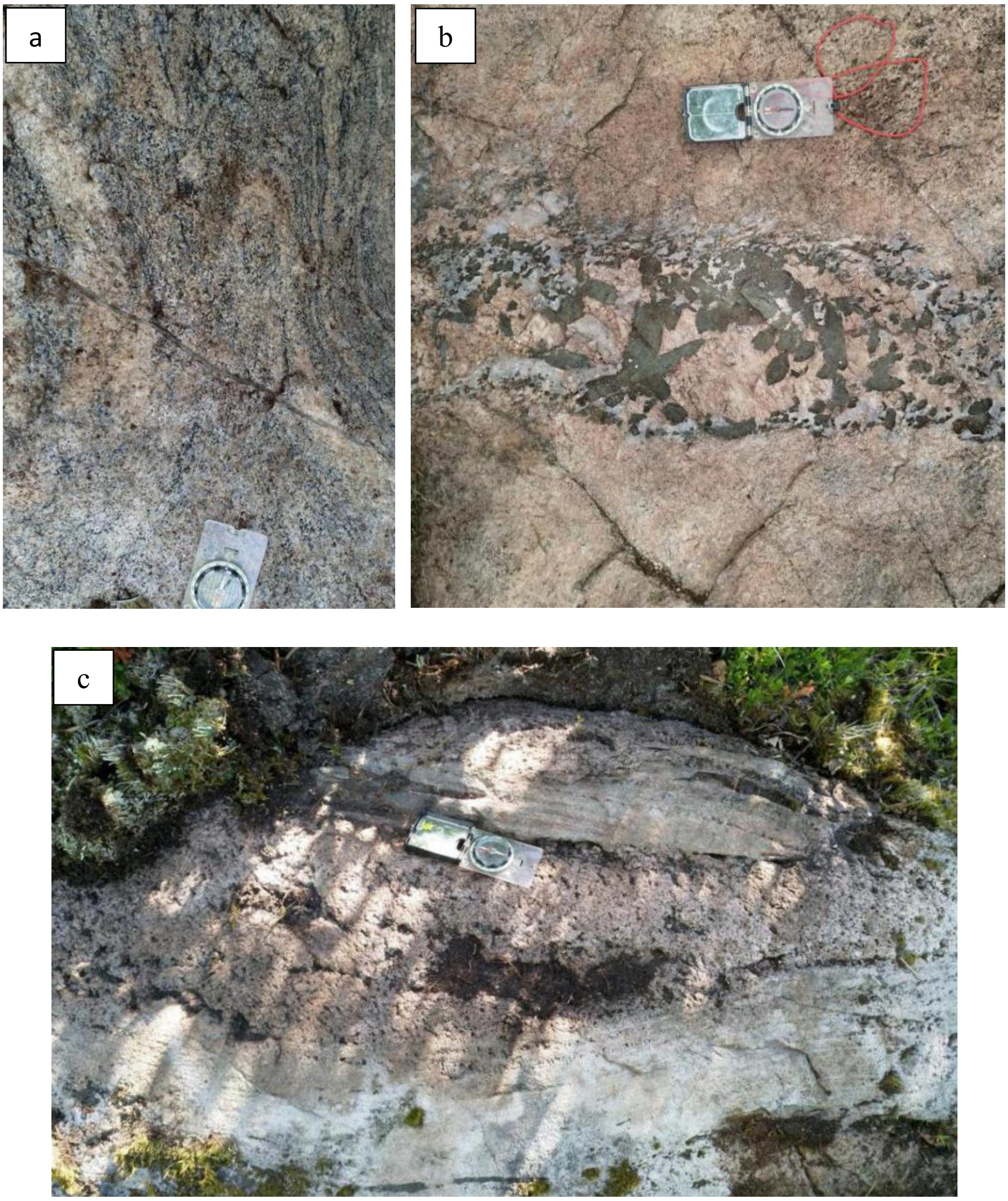


Figure 5. a) Gneissic banding in a fenite gneiss consisting of alkaline feldspar, pyroxene and quartz on outcrop SIKA-2018-46. b) A pegmatitic vein/dyke consisting of pyroxene, alkaline feldspar and quartz is cross-cutting a leucocratic less deformed gneiss on outcrop SIKA-2018-26. c) On outcrop SIKA-2018-41 the fenite consists of coarse-grained alkaline feldspar and pyroxene with minor magnetite and can be construed as a fenitic dyke. The gneissic parts both above and under the fenite are mineralogically similar to the surrounding gneiss but with minimal amounts of biotite.

5.1.3 Fenite near the intrusion

The fenite close to the intrusion (up to 100 metres) exhibits an igneous texture on the western branch. Grain sizes vary from medium to pegmatitic. The fenite is usually pale white or pale red in colour and is dominated by feldspars. The feldspars can exhibit a rimmed mantle-like texture with a brown rim and a creamy white core or vice versa (Fig. 6). Perthitic texture is also observed within these mantle-textured feldspars. Curiously, quartz can be found in locations no more than 50 metres from the carbonatite-glimmerite intrusion. The quartz is translucent and can vary from milky to blue in colour. Blue quartz is often in contact with a dark blue mafic mineral. The dark mafic mineral cannot be determined in the field. It is considered to be an amphibole since, in places, it can be close to fibrous. At these locations the texture is banded and lineation can be observed (Fig. 7a, 7b).

Figure 6. Mantle texture on feldspars on outcrop SIKA-2018-144.

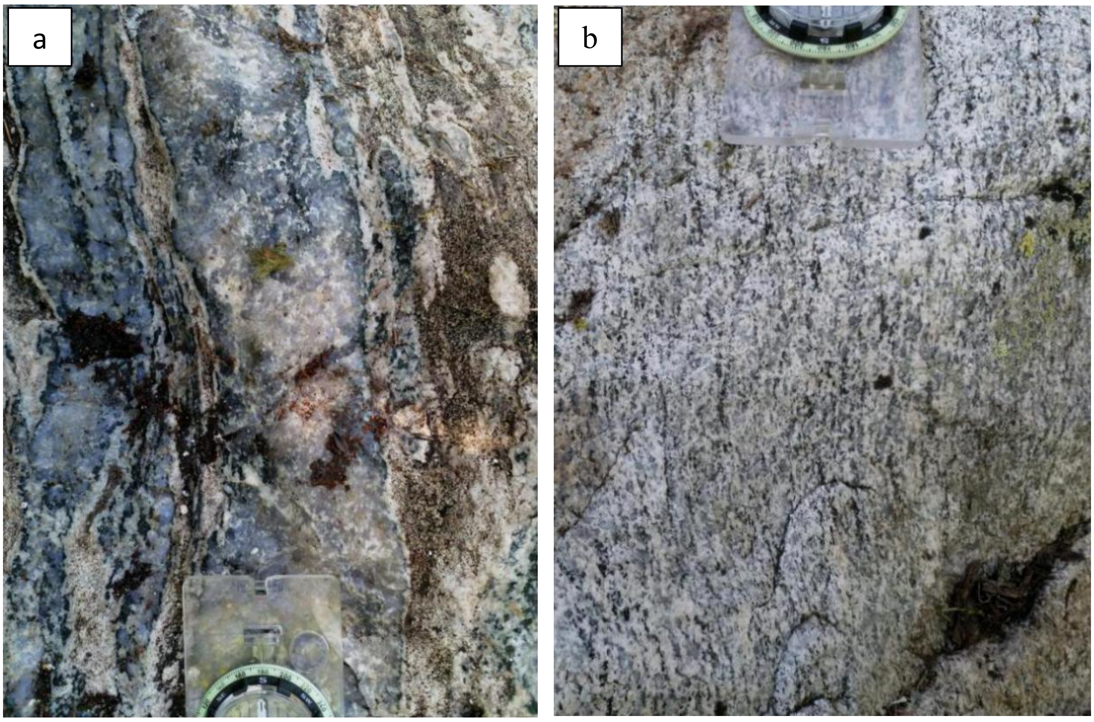


Figure 7. a) Opalescent blue quartz rimmed by dark blue amphibole. On the right of the photo there is pale feldspar and a dark mica. SIKA-2018-191 outcrop 100 metres from the intrusion. b) Elongated milky quartz (blue in places), feldspar and blue amphibole. SIKA-2018-195 outcrop is a mere metres from the intrusion.

The percentage of carbonate minerals in the fenite increases near the contact to the intrusion. The carbonates are deeply weathered and can only be detected by the chemical reaction between hydrochloric acid and carbonate. Within a few metres up to tens of metres from the intrusion the fenite is deeply weathered to the point were no sample can be gathered since the fenite breaks down to small pebbles and grains of feldspar (Fig. 8). At these places the soil can include laths of a dark mica.

Figure 8. Grains of feldspar from the fenite stuck on the soil at SIKA-2018-216 which is roughly 50 metres from the intrusion. Carbonates are also present at this and the surrounding outcrops.

In an area on the eastern fenite branch there are outcrops of fenite that display similar characteristics as the fenites proven to be within 100 meters from the carbonatite glimmerite intrusion. These fenites have feldspar with mantle texture and are rich in carbonates. Nearest outcrops of the carbonatite glimmerite intrusion to these fenites are two kilometres away.

5.1.4 Glimmerite

To find possible outcrops of carbonatite-glimmerite the technique of geobotanics was used because of the luxuriant and fern-rich vegetation that was found at every carbonatite-glimmerite outcrop (Fig. 9a). At these locations small streams and ditches filled with mica are common and the soil as well as the bedrock contain loose laths of mica in abundance (Fig. 9b).

Rocks belonging to the carbonatite-glimmerite intrusive body are only found on the western branch of the northern Siilinjärvi alkaline complex. Glimmerite is the only rock type belonging to the intrusion observed during field mapping. The glimmerite is dark to light brown sometimes with a red hue and consists a minimum of 80% of phlogopite. Along with the phlogopite there is blue amphibole, magnetite, apatite and carbonates. The three latter minerals are not found on all the outcrops (Fig. 10). The blue amphibole has been recognised previously in the mine to be richterite ($Na_2Ca(Mg,Fe)_5Si_8O_{22}(OH)_2$). However, the alkali composition of the blue amphiboles varies to such an extent that it may include different amphibole variants (O´Brien, 2015). The amphibole and magnetite-rich glimmerites are more coarse-grained and more resistant than the amphibole-poor glimmerites. They are therefore found at higher elevations and form steep ridges and cliffs similar to the metadiabase dykes in the area. Some glimmerites also contain sulfide minerals.

Figure 9. a) Glimmerite outcrop SIKA-2018-184 at a bottom of a ditch surrounded by lush fern-rich vegetation. The glimmerite contains phlogopite, blue amphibole, carbonates, apatite and sulphides. b) Amphibole and magnetite-rich glimmerite SIKA-2018-167. The brown phlogopite laths are clearly visible on the surface of the outcrop.

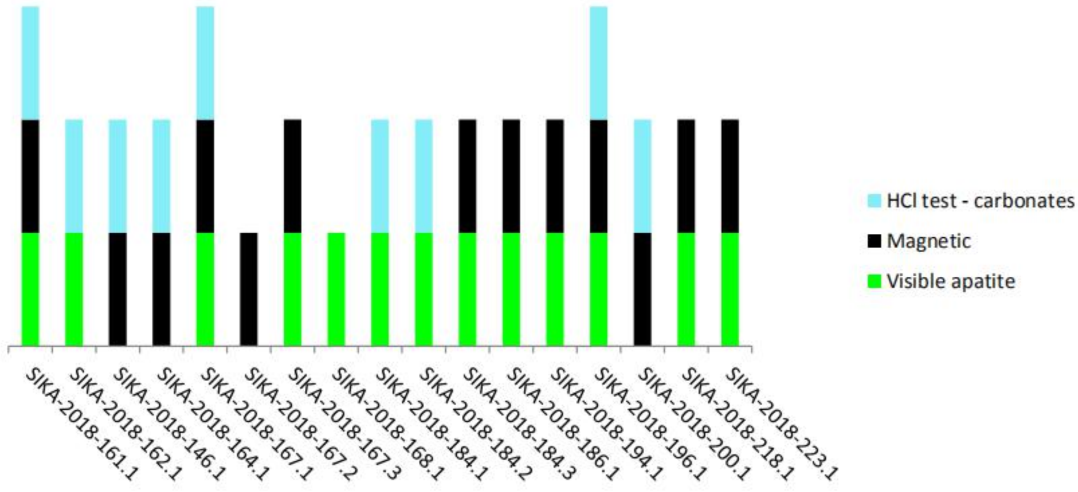


Figure 10. The three main glimmerite properties and outcrop IDs (SIKA) on which outcrops they occur.

5.1.5 Gneiss

The basement gneiss is characterised by gneissic banding with alternating felsic and mafic parts consisting of light coloured feldspar and quartz, and biotite and hornblende respectively (Fig. 11a). Quartz veins, granitic dykes and epidote filled cracks are common. At places the cracks are filled with magnetite. Migmatitic gneiss, which is the dominant rock type in the basement gneiss complex (Lukkarinen, 2008), was not observed during the mapping. West of the western branch the gneiss is more metasomatically altered. Epidotisation has affected large parts of the gneiss turning it pale green. Blue opalescent quartz is also observed (Fig. 11b).

Between the two branches belonging to the alkali complex is an unmetasomatised basement gneiss which belongs to the same suite as the surrounding gneisses. The gneiss between the two fenite branches is characterised by a network of quartz veinlets. A distinct shear zone is the main structure in this area and it can be tracked for hundreds of metres.

Figure 11. a) A typical gneiss in the area; slight gneissic banding and is dominated by the felsic minerals. SIKA-2018-67. b) Blue quartz and a heavily epidotised part of the western gneiss at SIKA-2018-113.

5.1.6 Metadiabase

The diabase dykes in the Siilinjärvi area are metamorphosed and are therefore named metadiabase. The dykes are dark green to dark brown in colour and consist mostly of plagioclase and hornblende. The orientation of the dykes varies between NW-SE to NNW-SSE and can sometimes be followed for hundreds of metres since the dykes form ridges in the terrain. The grain size varies from fine to medium and the texture is usually slightly lineated but can exhibit ophitic textures. Contact relations between the metadiabase dykes and the main lithologies are sharp. At places the contact is deeply sheared creating a tens of centimetres wide shear zone consisting of chlorite schist. Epidote veinlets and cracks are observed in the metadiabase dyke west of the alkaline complex (Fig. 12a). These are in places cut by later fractures. Enigmatic feldspar xenocrysts are observed in a clearly oriented metadiabase dyke in the eastern fenite branch (Fig. 12b).

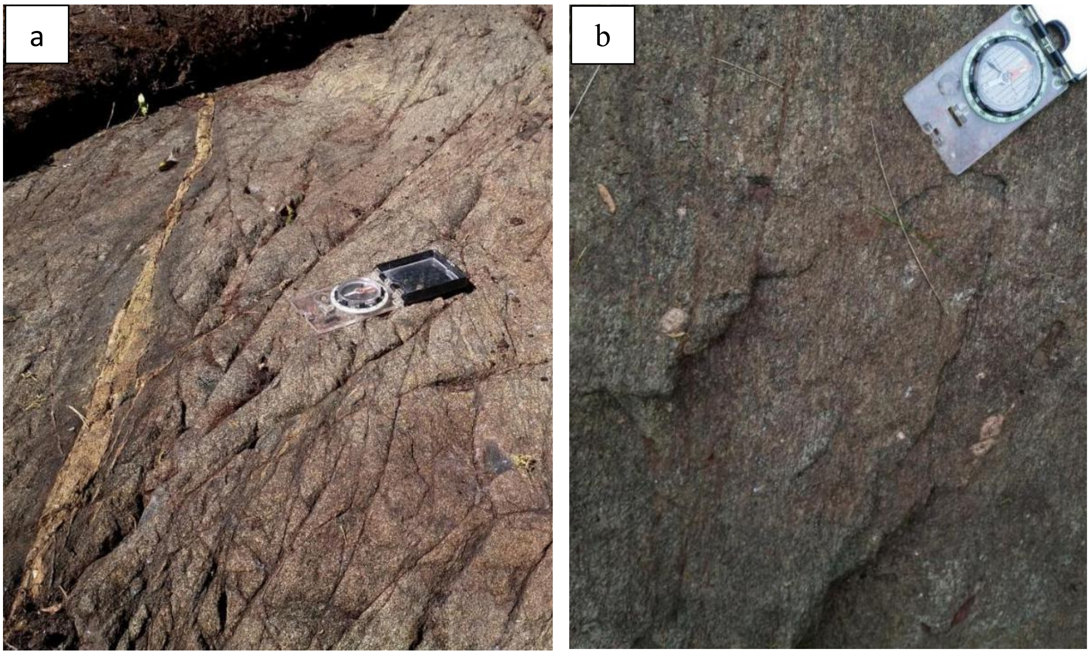


Figure 12. a) Lineated metadiabase with multiple epidote filled cracks west of the alkaline complex, SIKA-2018-135. b) A similarly lineated metadiabase, which includes feldspar xenocrysts in the eastern fenite branch, SIKA-2018-88.

5.1.7 Tectonic structures

Tectonic measurements can only be made in the gneiss, the fenite gneiss and rough contact areas formed by the cross-cutting metadiabases. A large shear zone is located in the gneiss between the two fenite branches. It is characterized by strong schistosity and unique mineralogy. Talc and chlorite layers are formed in the gneiss along with feldspar and quartz layers (Fig. 13). The schistosity has a N-S direction with a median dip/dip direction of 70/270. This direction and dip is similar in the gneissic banding and foliation across the entire northern alkali complex with minor local variations. Lineation or foliation was observed at a few glimmerite outcrops. They have a shallow dip of 40^{o} to the north east instead of a steep dip towards west as in the other lithologies.

Figure 13. Photo from outcrop SIKA-2018-71 of the sheared chlorite schist with a pale green talk layer on the left-hand side.

5.2 Micro-XRF analysis

Micro-XRF analysis was conducted of eleven samples. Seven thin sections were prepared out of the eleven samples in an effort to combine µXRF results with petrographic microscopy results. The samples chosen for analysis are from different key areas in the mapped fenite lithology. They were chosen not only on a geographical basis but also based on their wide-ranging appearance and field relations to the carbonatite-glimmerite (Fig. 14). Pale white fenites and red fenites were analysed, as were the fenites with macroscopic mantle texture and blue opalescent quartz. Along with the fenite samples one glimmerite sample was also analysed.

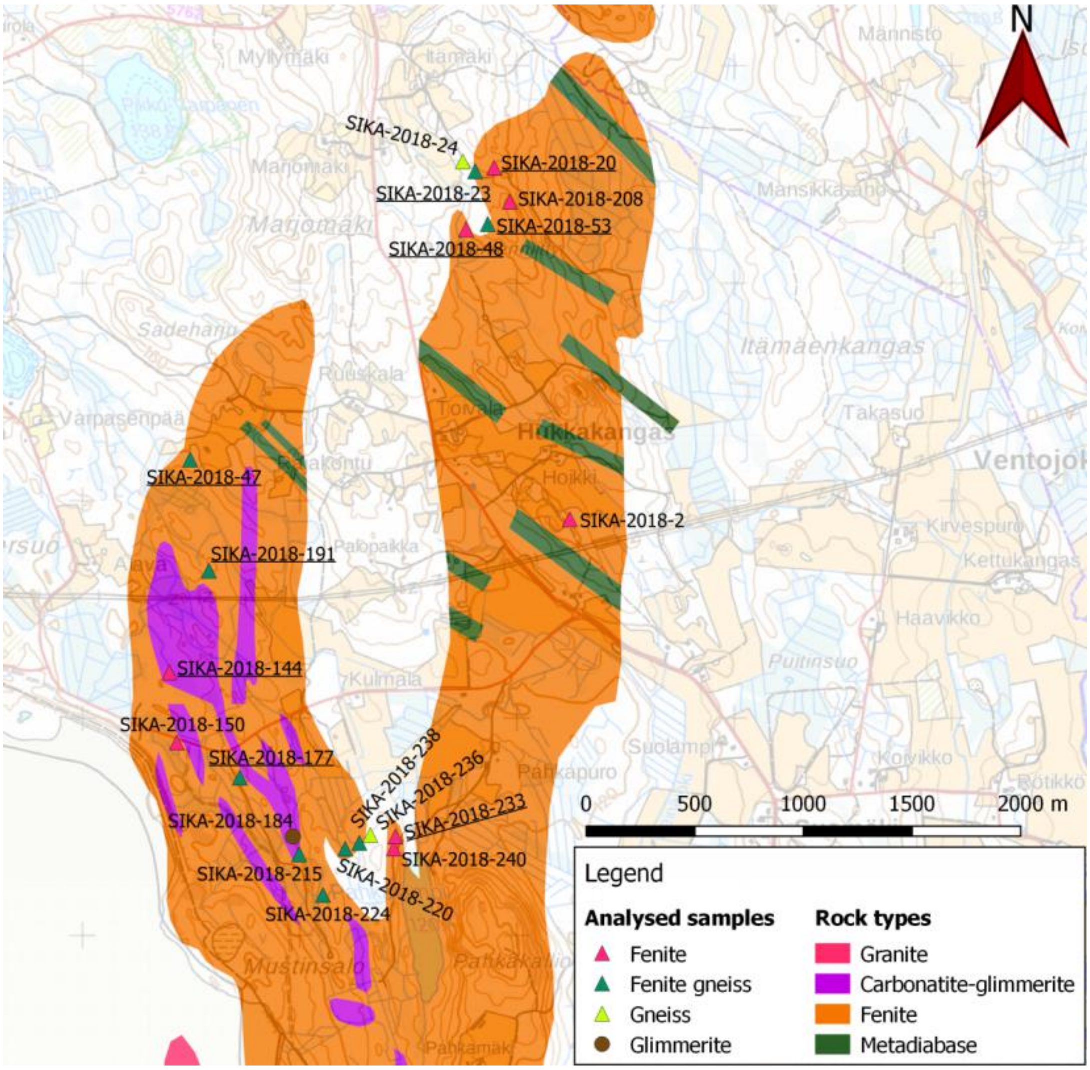


Figure 14. Lithological map of the northern Siilinjärvi alkali complex with thin section and µXRF sample points. The underlined sample IDs signify µXRF analysed samples.

The main goal of the µXRF analysis was to determine the type of fenitisation along with the distribution of mobile elements typical to the process of fenitisation. The analysis of the main components of fenitisation, i.e. Na and K, show that Na can only be found in trace amounts while K is the dominant element in the alkaline feldspars and one of the most abundant elements in every fenite sample analysed. In figure 15 the quantity of K and Na is visualised in the µXRF analysis. The grainy and washed out visualisation of Na is because of the low Na amounts in the samples as well as the element's physical properties, e.g. atomic mass. In contrast, the visualisation of K is clear and sharp. This signifies high quantities of the element. Grain boundaries are also distinct in the analysis which is consistent with the distribution and grain sizes of the alkaline feldspars in the samples.

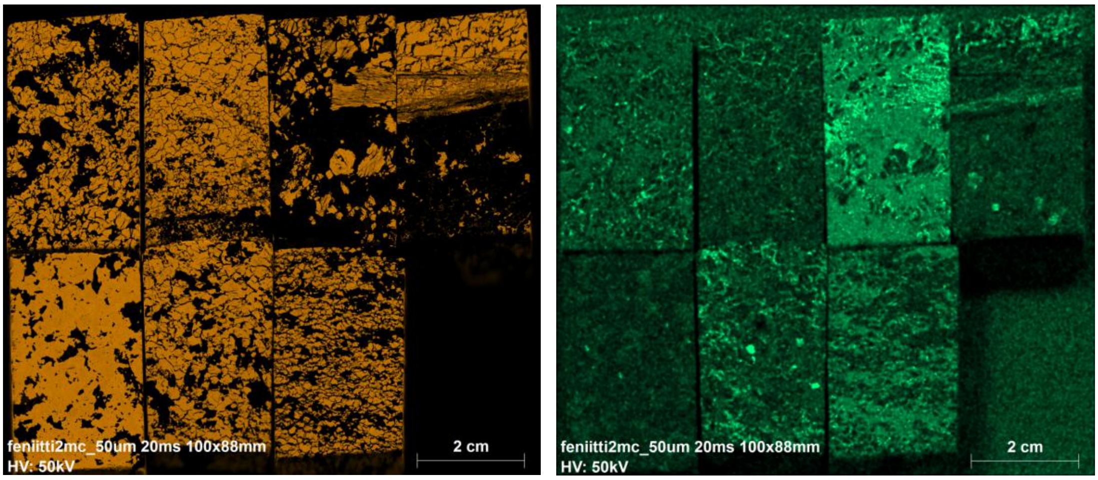


Figure 15. On the left is a µXRF analysis "map" of the distribution and relative quantity of K (orange). And on the right a µXRF analysis map showing the distribution of Na (green) within the same samples. Notice the scattering of Na on the lower right corner where there's no sample.

5.2.1 Mafic minerals

The green mafic minerals analysed with the µXRF software are clinopyroxenes belonging to the aegirine-augite series. This is confirmed by the petrographic analysis. The dominating mafic minerals contain varying amounts of Fe, Mg and Ca (Fig. 16). Sodium is also present in most of the analysed mafic minerals but not in significant amounts. The complex composition of aegirine-augite means a wide variety of small compositional variations and element substitution within an aegirine-augite grain is expected. In samples SIKA-2018-53.1 and SIKA-2018-177.1 there are significant Mg anomalies within the mafic minerals. The anomaly shows an uneven distribution of Mg in the mafic minerals, suggesting that portions of the aegirine-augite are enriched in the augite component (Fig. 16). The high amount of Ca and low amount of Na in the element analysis supports the notion that the clinopyroxene is augite dominated. Elevated amounts of Na is evident in only one sample (SIKA-2018-191.1). Here the amount of Ca is significantly lower than in the other samples, implicating a sodium-rich amphibole to be the dominant mafic mineral.

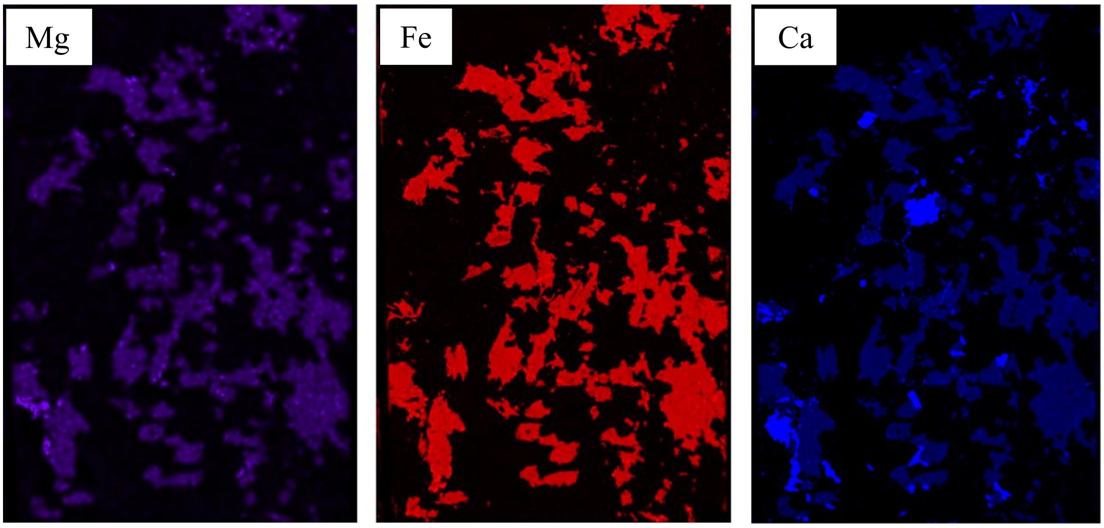


Figure 16. Mg, Fe and Ca displayed on µXRF maps of SIKA-2018-23.1. All the minerals giving off a signal are clinopyroxenes, except for the bright blue Ca anomalies, which are carbonates. The grainy Mg signatures are due to the light atomic mass of Mg and limitations of the µXRF method to accurately estimate the content and placement of lighter elements.

5.2.2 Element distribution in feldspars

Macroscopic mantle texture in alkaline feldspars, which is visible in samples SIKA-2018-144.1, SIKA-2018-144.1.2 and SIKA-2018-177.1, are characterised by a dark gray to brown-coloured core and a pale white rim. This texture is also visible in the µXRF when Ti (titanium) and Sr (strontium) are displayed with the µXRFsoftware (Fig. 17). The µXRF map shows the alkaline feldspar rims depleted of these elements or, in contrast, a core enriched in Ti, Sr and Ba (barium). The amount of these elements is small but geochemical analysis shows an up to ten-fold depletion of Ti from core to rim (Fig. 18). Other than this anomaly, these samples exhibit very even distribution of potassium in the feldspars with insignificant amounts of sodium and calcium. A µXRF map of SIKA-2018-177.1 with Ba is included in Appendix D.

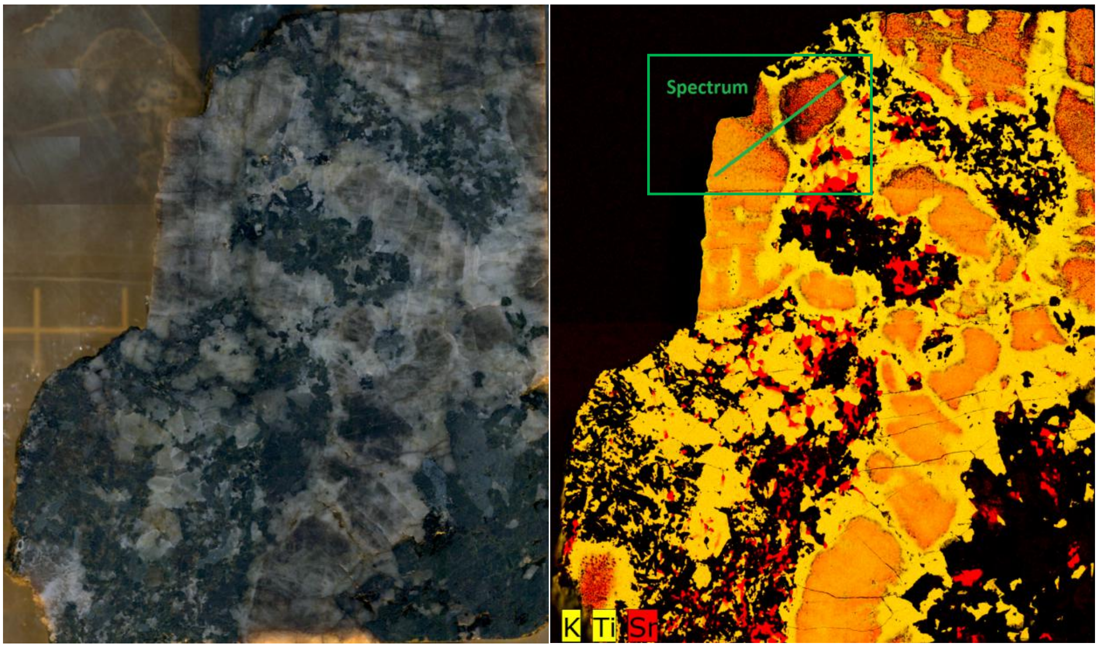
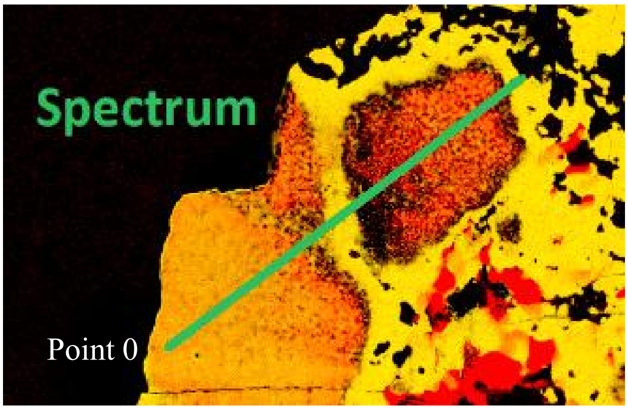


Figure 17. A photo and a µXRF map displaying the distribution of K, Ti and Sr in SIKA-2018-144.1. The area with different shades of yellow are grains of alkaline feldspar with an even distribution of K. The dark yellow anomalies represent Sr and Ti enriched alkaline feldspar, which is evident in the spectrum analysed alkaline feldspar grains within the green box (Fig. 18). The red anomalies outside of the alkaline feldspars are calcites which contain strontium.



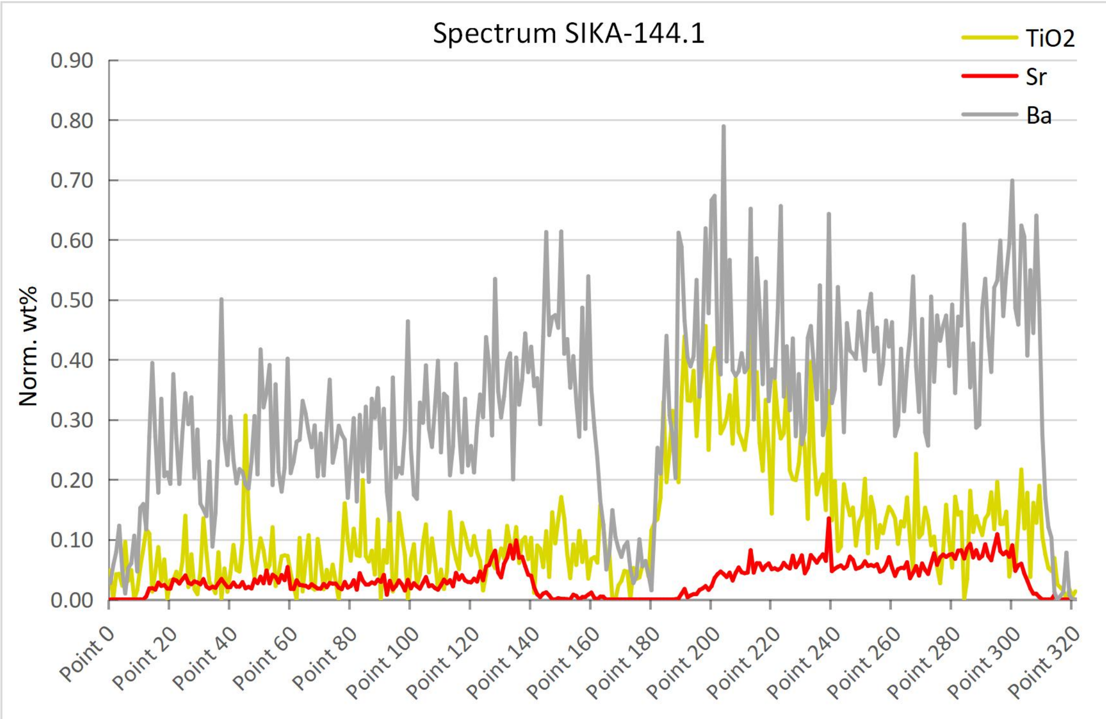


Figure 18. The spectrum line analysis results of two alkaline feldspars from SIKA-2018-144.1 show a sharp decrease of TiO_2, Sr and Ba around point 150 and an increase at point 190. This area of decreased TiO_2, Sr and Ba content is the rim and contact area of two alkaline feldspars. The spectrum line is ca. 2.2 cm long.

The potassium distribution map generated shows distinct abrupt feldspar grain edges on samples SIKA-2018-20.1, -23.1, -47.1, -53.1, -233.1 and a less noticeable but a similar pattern on samples SIKA-2018-48.1 and SIKA-2018-191.1. The feldspar grains appear to be separated by a network of veinlets between the grains. The distribution of aluminium and silica stays the same but there is a significant loss of potassium and an increase of Na content around the rims of the feldspars (Fig. 19).

Because of an even distribution of Al and Si, it is assumed that feldspar with high albite content is rimming the potassic feldspar (microcline or orthoclase). Albite-rimmed microcline has been observed in some potassic fenites around the world (Le Bas, 2008). This implies a late sodium enrichment in the fenitising fluid which has affected only the rims of the potassic feldspars and caused albitisation (Fig. 20).

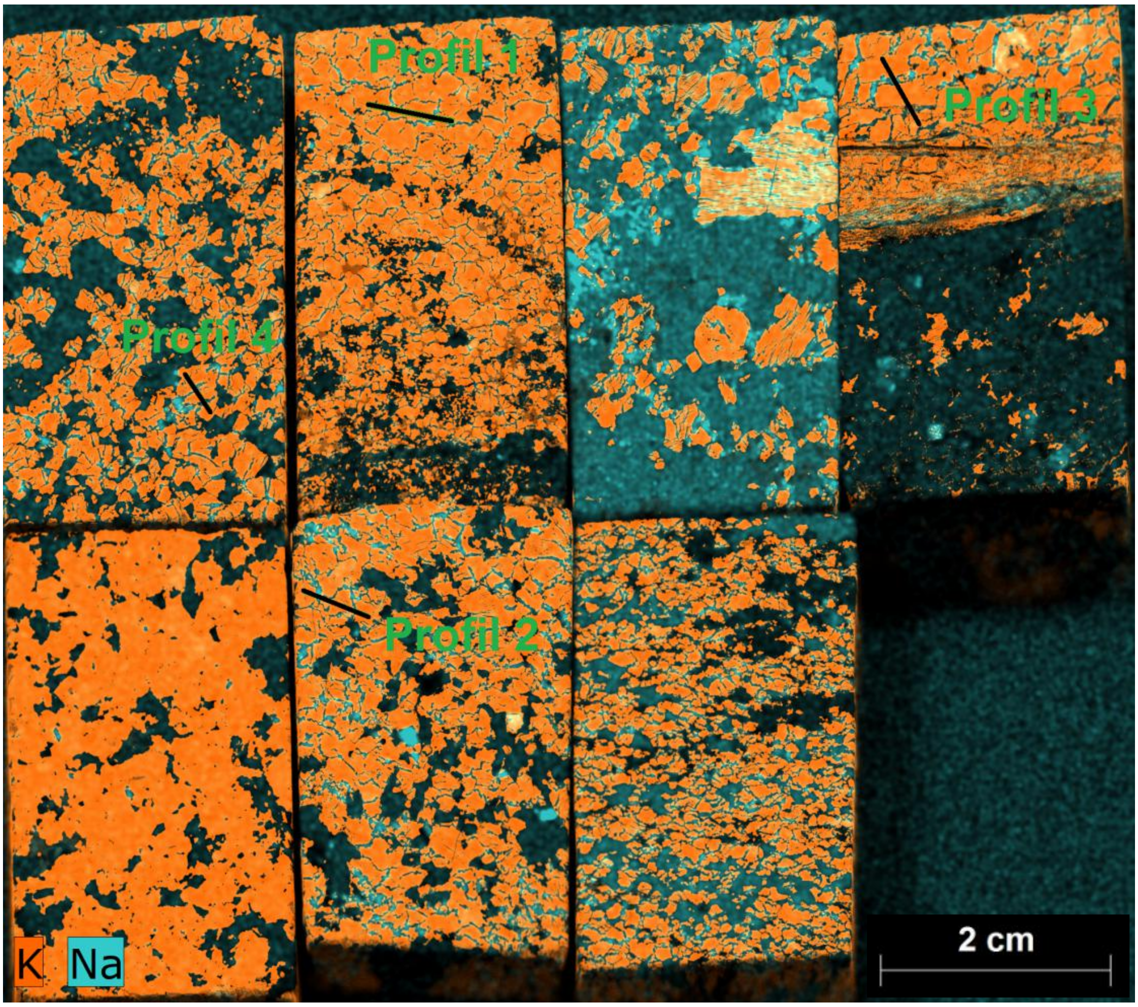
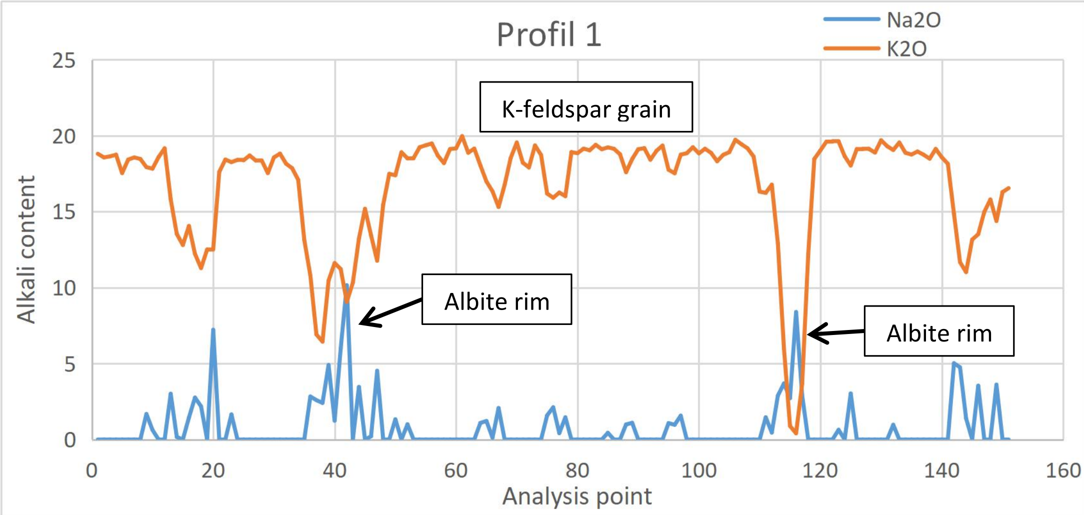
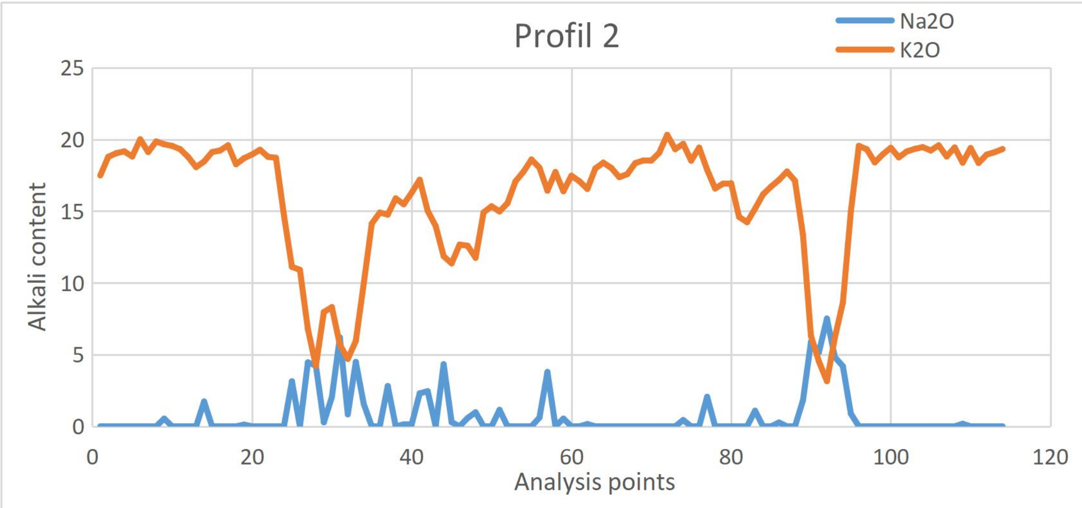
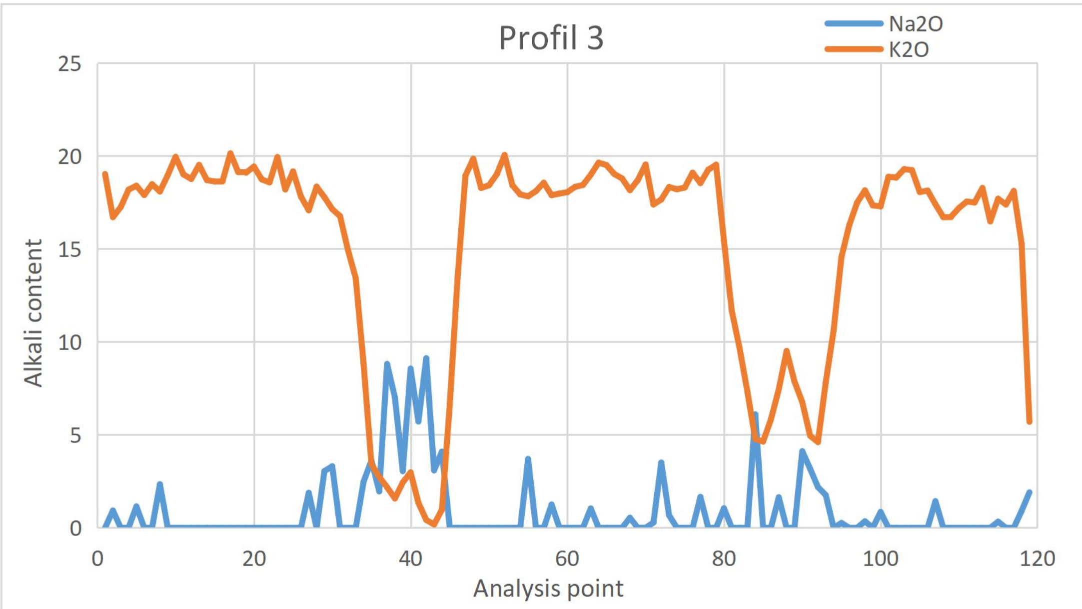


Figure 19. Potassium (orange) and sodium (teal) displayed simultaneously with four spectrum line analysis profiles (‘Profil’ 1-4) conducted across alkaline feldspar grains.


Profil 1
Na2O
K2O
K-feldspar grain
Albite rim
Albite rim
Alkali content
Analysis point
0
5
10
15
20
25
0
20
40
60
80
100
120
140
160


Profil 2
Na2O
K2O
Alkali content
Analysis points
0
5
10
15
20
25
0
20
40
60
80
100
120


Profil 3
Na2O
K2O
Alkali content
Analysis point
0
5
10
15
20
25
0
20
40
60
80
100
120

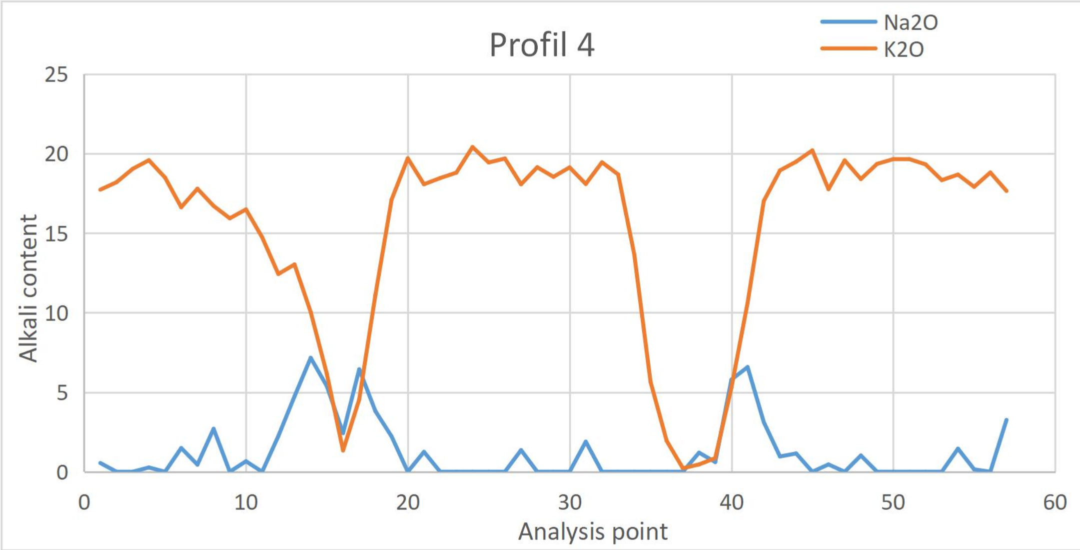


Figure 20. Spectrum line analysis results of the albite-rimmed alkaline feldspars from figure 19. The K-content sharply drops around the edges of the alkaline feldspar where albite is present. This is displayed by the increase in Na-content as illustrated in Profil 1. The three other spectrum line graphs share the same pattern with Profil 1.

In sample SIKA-2018-191.1 the alkaline feldspars have undergone exsolution. It is the only micro-XRF analysed sample where extensive perthitisation can be visualised in a µXRF map. The exsolution lamellae can be visualised in a line chart where the albite content (Na) increases when the K content decreases (Fig. 21). The perthites in the same sample also display a corona texture, with Ti and Sr enriched cores, as in sample SIKA-2018-144.1 (Fig. 17).

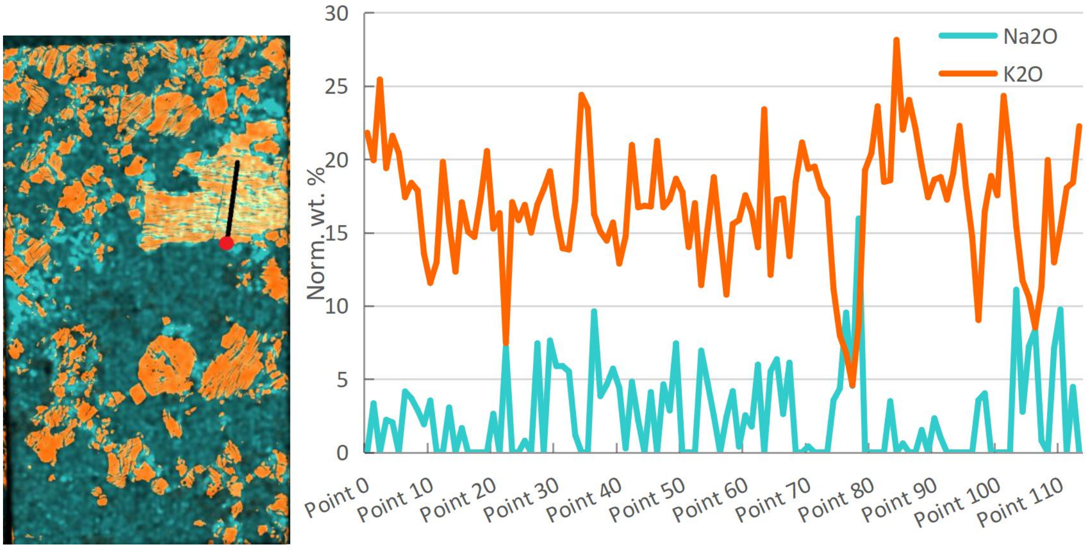


Figure 21. Spectrum line analysis of a well developed perthite from sample SIKA-2018-191.1. Point 0 is at the red dot on the µXRF map where orange is K and teal is Na. The spectrum line is ca. 0.9 cm long.

5.3 Thin section analysis

Petrographic and mineralogical analysis of the samples were done by analysing them under a petrographic microscope. Fifteen thin sections representing different fenites were prepared together with one gneiss and one glimmerite thin section sample. The main minerals in the fifteen fenite thin sections are alkaline feldspar and clinopyroxene. In individual fenite thin sections the main minerals can include amphibole, quartz and calcite. Common accessory minerals are apatite, calcite, plagioclase, titanite and opaques.

5.3.1 Clinopyroxene

The clinopyroxene is determined to be aegirine-augite because of its dark green to pale green pleochroism. This observation is supported by previous studies made of the Siilinjärvi fenites (Puustinen, 1971 & Härmälä, 1981). It exists in all but three thin sections and is an accessory mineral in only one thin section. The aegirine-augite occurs mostly as mineral aggregates and clusters (Fig. 22). Some of the grains are altered resulting in a blue amphibole corona around a single grain or the entire augirine-augite cluster. The process of a pyroxene alteration resulting in an amphibole is called uralitisation. Opaques, titanite and apatite inclusions can occur in the pyroxene.

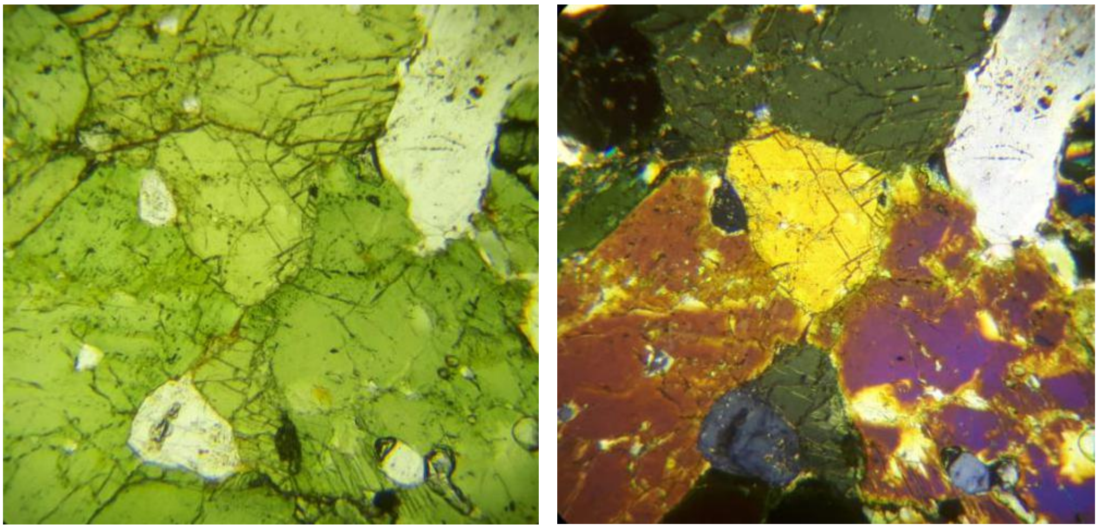


Figure 22. An aegirine-augite aggregate in sample SIKA-2018-224.1 in both PPL (plane polarised light) and XPL (cross polarised light). The green minerals are aegirine-augite and the pale minerals are alkaline feldspar. Width of the frame is 1.0 mm.

5.3.2 Alkaline feldspar

The alkaline feldspar is most notably microcline and orthoclase. It has formed as a product of plagioclase and primary K-feldspar breakdown. Varying intensities of microcline cross-hatching is observed. Orthoclase can be difficult to distinguish because of the different alterations leading to a turbiditic characteristic of the mineral, which is absent in primary K-feldspars. There are many structures and textures that are imprinted on the alkaline feldspars, fracturing and chessboard twinning along with textures related to pressure solution. Perthite is present in inconsistent amounts. It can be highly distinguishable or barely visible (Fig. 23a). Perthite is consistently present together with chessboard twinning, also known as chessboard albite (Fig. 23b).

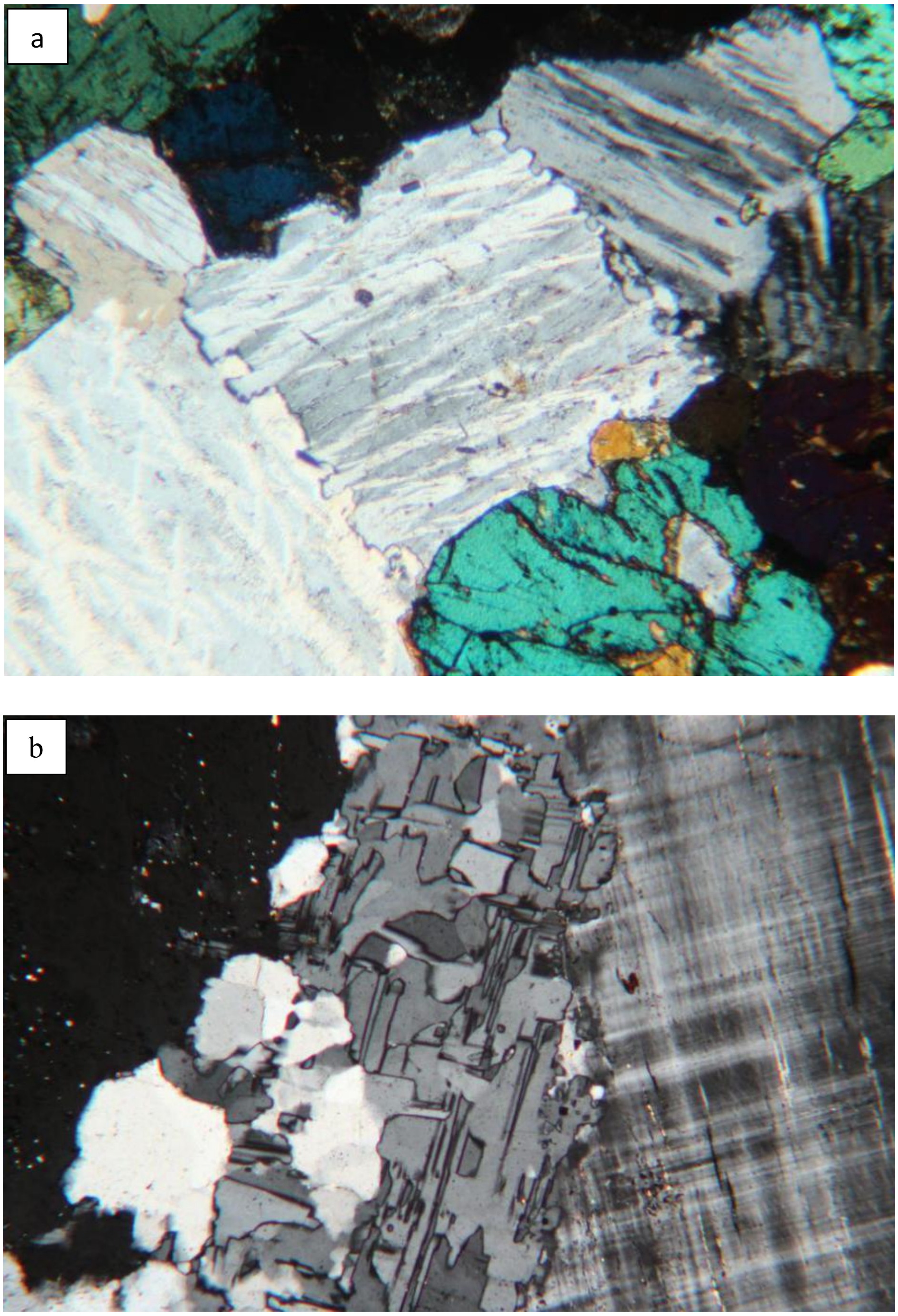


Figure 23. a) A perthitic alkaline feldspar with sutured margins to the nearby identical alkaline feldspars in XPL. These are surrounded by aegirine-augite, sample SIKA-2018-224.1. b) Chessboard albitisation between a microcline with slight perthitisation (right) and an alkaline feldspar (left), sample SIKA-2018-23.1. Width of both frames is 0.8 mm.

Na-rimmed texture that is visible in the μXRF analysis maps is also observed in the petrographic microscope. The rims of the alkaline feldspars, usually microcline, are crowded by smaller grains of a more unturbidised feldspar i.e. an undisturbed feldspar. It has a similar appearance to the uralitic texture formed by Na-amphiboles found on multiple pyroxene grains. Some of the unturbidised feldspars display albite twinning and can even form a complex chessboard albite texture (Fig. 24). Calcite and quartz can also rim the alkaline feldspars.

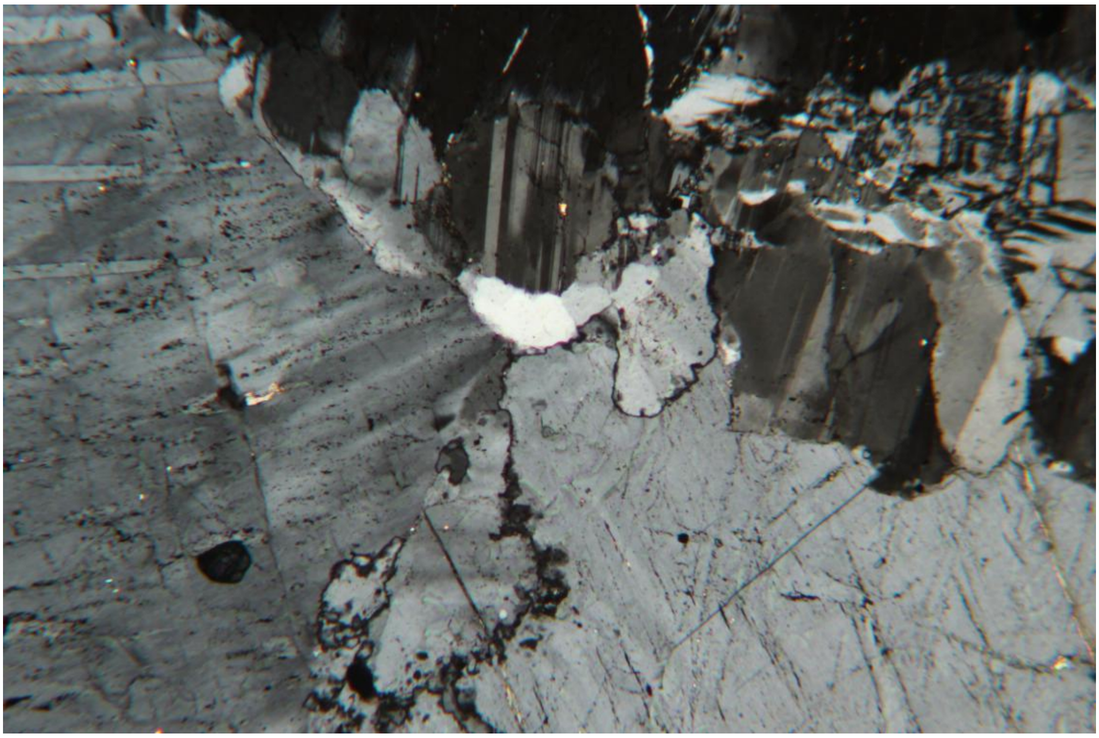


Figure 24. Large alkaline feldspar grains with sutured margins and plagioclase together with albitisation texture (upper right hand corner) in sample SIKA-2018-23.1. Width of the frame is 1.2 mm.

The mantle-textured alkaline feldspars observed in the field do not display a similar texture in thin section e.g. SIKA-2018-177.1. In thin section the feldspars display cross-hatching (microcline) and perthitic textures. The feldspars have small inclusions of high interference coloured minerals some of which are identified as carbonates and micas. These inclusions are concentrated in the core of the feldspars along with turbiditic microtextures. The rims of the feldspars are mostly devoid of the inclusion (Fig. 25).

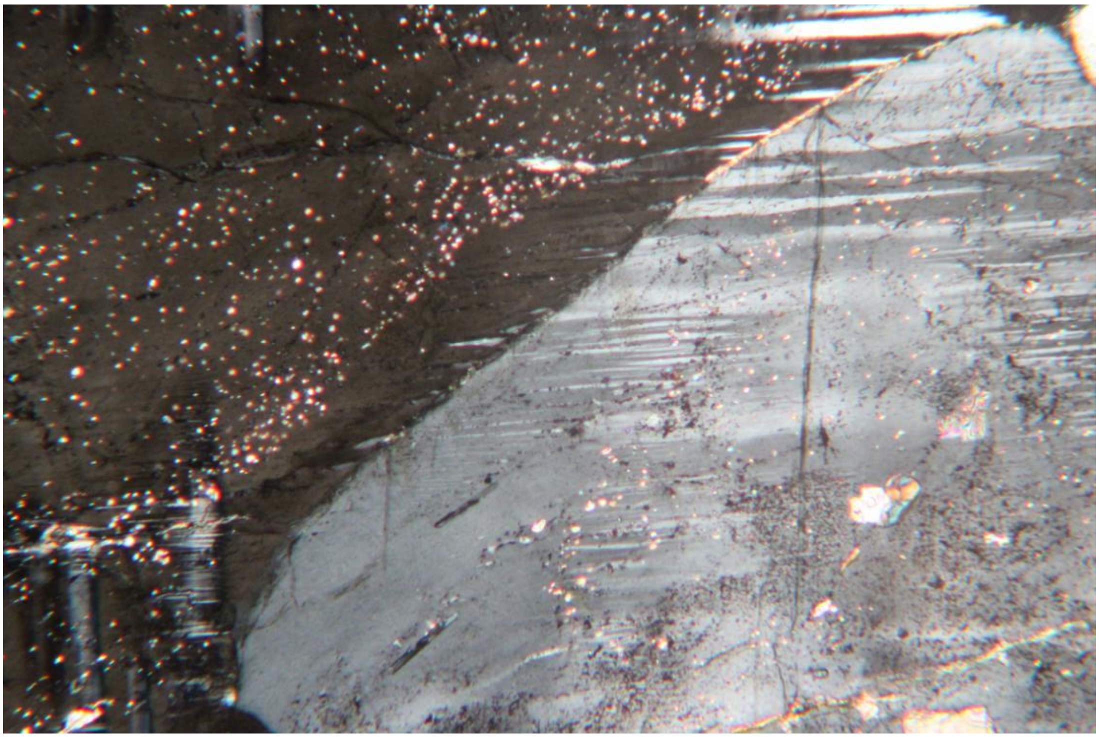


Figure 25. Inclusions in mantle-textured feldspars (here microcline) in sample SIKA-2018-177.1. Width of the frame is 1.2 mm.

5.3.3 Amphibole

The amphibole in the fenites is mostly blue to dark blue but can also be blue-green pleochroic. It can be found in almost all fenite thin sections but only as a main mineral in fenites with minor or no aegirine-augite. The blue amphibole exists together with the aegirine-augite and can form a corona-like texture around the aegirine-augite grains due to uralitisation (Fig. 26). This aegirine-augite to blue amphibole reaction is also evident along fractures within aegirine-augite grains. The Na-rich fluids have travelled along these fractures and altered the pyroxenes in the immediate vicinity into blue amphiboles. Na-amphibole replacing pyroxene could be evidence of two separate fenitisation events (Verschure & Maijer, 2005). The blue amphibole is presumed to be either richterite or riebeckite, since those amphiboles are fairly common in the carbonatite glimmerite intrusion (Härmälä, 1981 & O'Brien, 2015). The amphibole also forms a pseudomorph of a mica.

Pure blue amphibole grains with no contact to pyroxene is found in four thin sections. The most notable of these being in sample SIKA-2018-191.1. Here the blue amphibole is rounded and has a cloudy core (Fig. 27). The characteristic 120^{o} cleavage in amphiboles is visible in samples SIKA-2018-47.1 and SIKA-2018-150.1. The blue amphibole in these samples is subhedral and can occur together with the pyroxene.

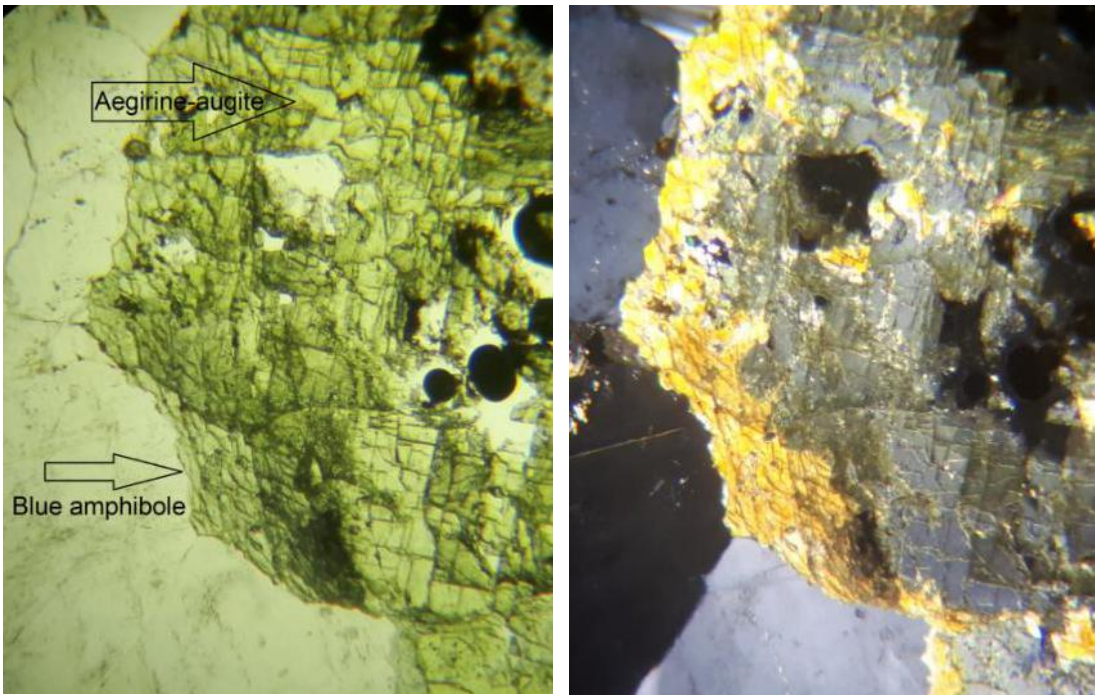


Figure 26. Blue amphibole surrounding the aegirine-augite grain in sample SIKA-2018-150.1 in both PPL and XPL. The minerals on the left side of the frames are orthoclase. Width of the frame is 1.0 mm

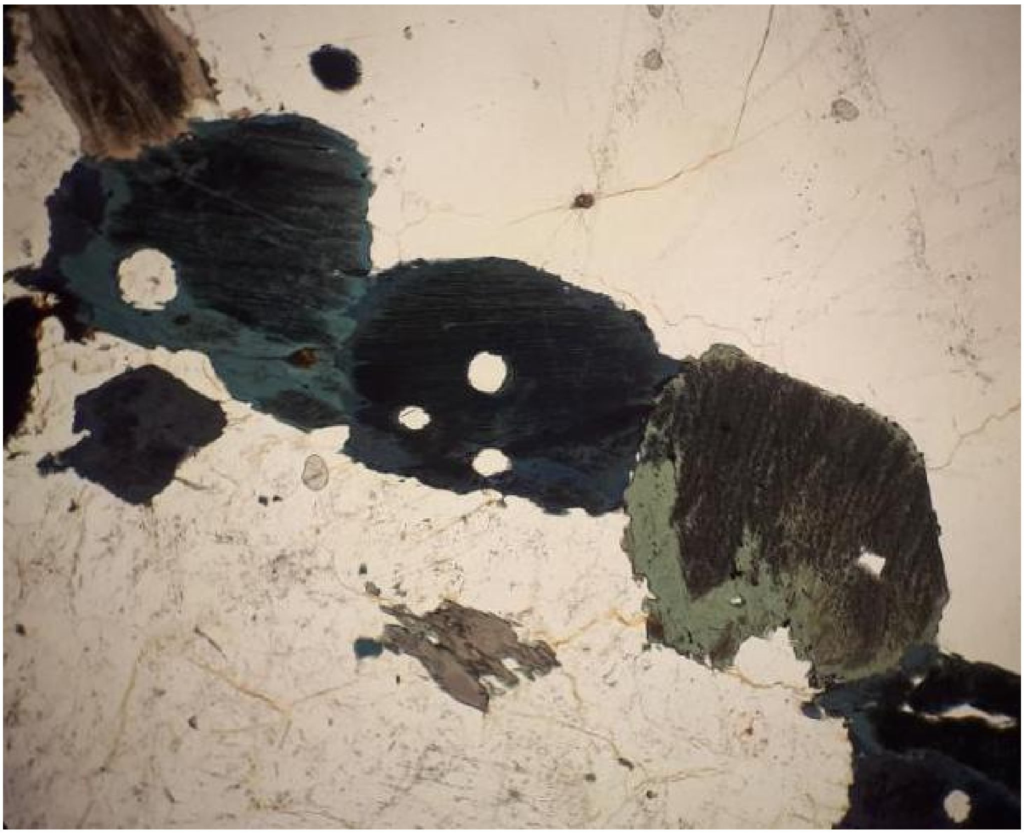


Figure 27. Rounded blue amphibole grains in sample SIKA-2018-191.1. The deep blue colour and intense pleochroism suggests that these amphiboles are riebeckites. Width of the frame is 1.5 mm.

5.3.4 Accessory minerals

Quartz can be absent or a main mineral in the fenite thin sections. It displays consistent textures such as undulation and dynamic recrystallisation throughout all the thin sections quartz is present in. According to Bardina & Popov (1994) silica does not need to be mobile during the course of fenitisation. If the protolith has a low silica content the process of fenitisation may increase the amount of silica respective to the protolith (Elliot et al., 2018).

Calcite exists in all but one thin section. It occurs as individual grains and aggregates. Calcite together with quartz can also occur around the edges of other minerals and sometimes surround them completely (Fig. 28). Calcite is considered as an uncommon mineral in fenites (Zharikov, 2007). However, it is commonly found in fenites formed by carbonatites. This is evident in the Fen (Norway) and Alnö

(Sweden) fenites, where fenitsation caused by melteigite-ijolite series rocks contain only tiny amounts of calcite while carbonatite induced fenites contain larger amounts of calcite (Morogan & Woolley, 1988; Morogan, 1994).

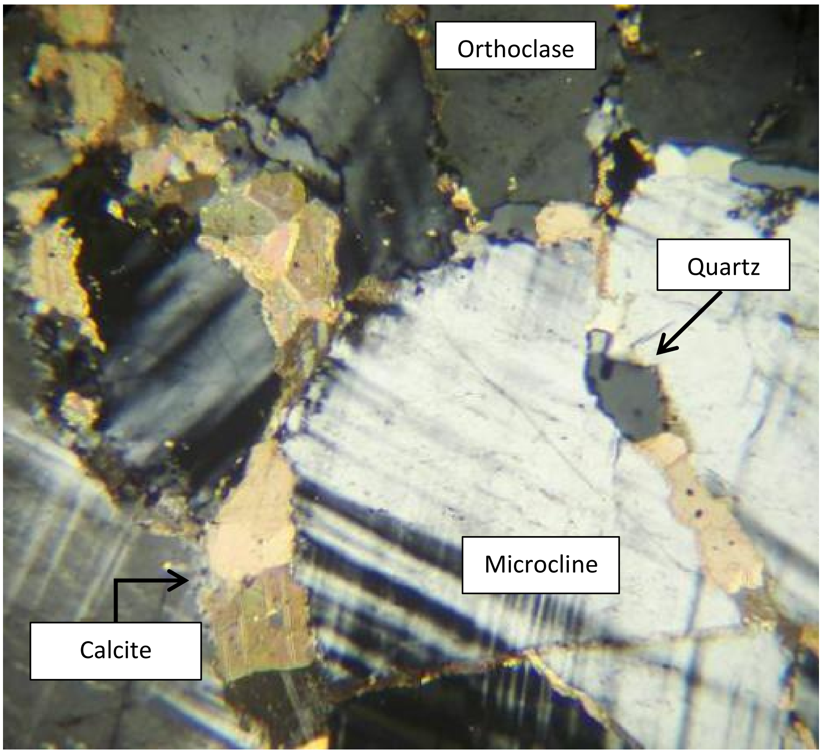


Figure 28. Calcite and quartz surrounding microcline and ortoclase grains in SIKA-2018-208.1 in XPL. Width of the frame is 1.0 mm.

Titanite is present in minor to moderate amounts in five thin sections. The largest amounts of titanite is found in thin section samples taken of fenites affected by the SE-NW shearing typical to the area.

Dark mica is present in the basement gneiss thin section as expected and is presumably biotite. In fenite sample SIKA-2018-47.1 the primary biotite is present. Phlogopite is observed in sample SIKA-2018-220.1 it occurs together with blue amphibole but not with the pyroxene.

Opaques are present in 11 out of 15 thin sections. The opaque minerals are assumed to be magnetite and ilmenite, both of which were observed in the field. The opaques are situated sparsely in most of the thin sections but in samples SIKA-2018-53.1, 208.1 and 215.1 the opaques occur together with either aegirine-augite or the blue amphibole. Ilmenite is recognised by the TiO2 pseudomorph leucoxene (Fig. 29).

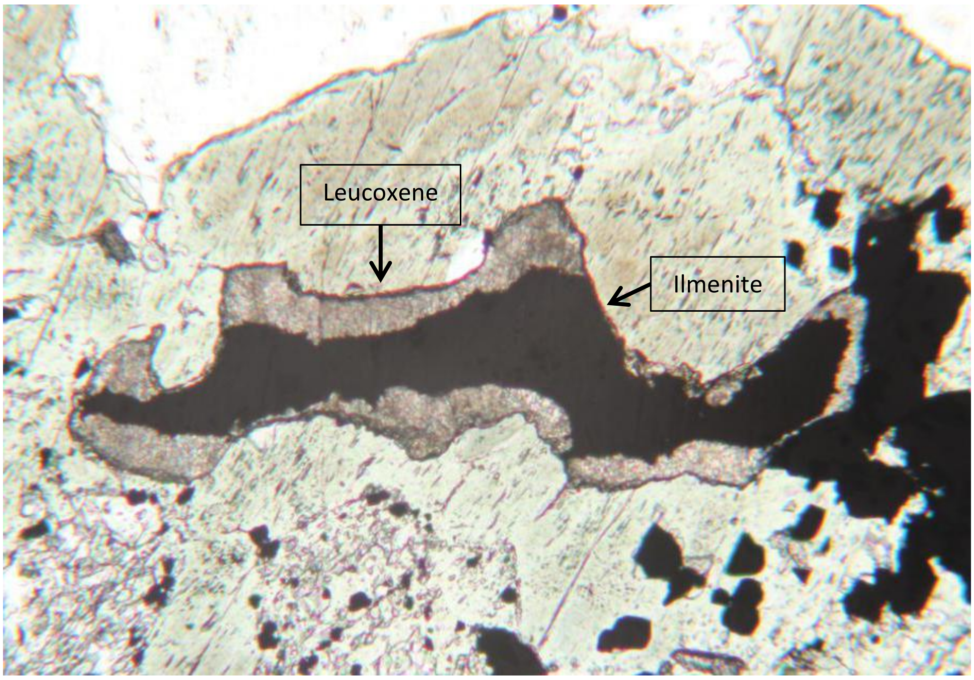


Figure 29. Leucoxene after ilmenite within an altered pyroxene along with other opaques in SIKA-2018-53.1.

6 Discussion

Potassic fenitisation is the main type of fenitisation observed in the northern part of the Siilinjärvi alkali complex. The majority of carbonatite complexes around the world have a potassic fenite halo and as such the K-fenitisation is expected (Elliot et al. 2018). However, most of the samples studied have displayed fenitisation where both alkalis (K and Na) have been mobile. Even in extreme cases of K and Na fenites respectively, there are evidence of both alkalis being active during the metasomatisation of the wall rock (Le Bas, 2008).

6.1 K-fenitisation

The main feldspars observed in the samples and in the field are microcline, orthoclase and perthite, which are the results of K-fenitisation in the northern part of the Siilinjärvi alkali complex. The prevalent mafic minerals during pure K-fenitisation are clinopyroxene and Fe-oxides (Le Bas, 2008). Both of these minerals are observed in the field and in thin sections respectively.

Fenite xenoliths within the Siilinjärvi carbonatite-glimmerite intrusion could have been formed by hydraulic fracturing caused by the potassic fenitic fluids before the emplacement of the intrusion. Fenitic breccias along with fractures and cracks are more common around potassic fenites than sodic fenites (Le Bas, 2008). The fenite xenoliths in Siilinjärvi are mantled by phlogopite, which is of magmatic origin. Phlogopitisation is characteristic for K-fenitisation. The H_2O-rich fluids that caused the fenitisation at Siilinjärvi are also connected to phlogopite growth evident between carbonatite and country rock (Poutiainen, 1995; Le Bas, 2008). This could indicate that some of the glimmerite in Siilinjärvi is formed due to alkali metasomatism. Intriguingly, Le Bas (2008) suggests that the source for the K-rich fenitising fluids could be a phlogopite-bearing mantle, from which the carbonatite magma has derived. Fenite outcrops, closest to the glimmerite outcrops, also display a potassic fenitisation since the fenite consists mostly of alkaline feldspar. In sample SIKA-2018-220.1 phlogopite is present suggesting high-grade fenitisation or even contact fenitisation.

Veinlets and cracks filled with carbonates are a sign of K-fenitisation. The CO_2-rich fluids cause brecciation and cracks through which the fenitising fluids propagate. Carbonates therefore form within the microfractures, which are visible in e.g. sample SIKA-2018-208.1. Widespread K-fenitisation is induced by CO_2-rich fluids where K is partitioned into alkaline feldspars (Rubie & Gunter, 1983). High CO_2-content fluids are present in fluid inclusions found in early formed zircons at Siilinjärvi (Poutiainen, 1995).

6.2 Na-fenitisation

In many samples there is a depletion of K and an increase of Na content around the potassic feldspars, forming a corona texture. In these samples albitisation has affected the microcline and orthoclase. This has caused chessboard albite and small albite grains to form on the rims of the K-feldspar. Similar albite-rimmed alkaline feldspars have been observed in other potassic fenites in for example Silai Patti, Pakistan and Ruri Hills, Kenya (Le Bas, 2008). In sodic fenites at Iivaara, Finland, the secondary alkaline feldspar is rimmed by Na-rich feldspar. In high-grade fenites at Iivara the corona texture remains during the Na-enrichment of the cores of the alkaline feldspars (Sindern and Kramm, 2000). This further sodic-fenitisation does not take place in Siilinjärvi.

A similar rimmed texture of the aegirine-augite is observed in multiple thin sections. On the edges of the pyroxene the aegirine-augite has altered to a blue amphibole causing a uralitic texture. The amphibole is presumed to be Na-rich since the uralitic texture is also found in the most Na-rich sample SIKA-2018-191.1. Even though the uralitic texture is also present in the same samples as the albitised alkaline feldspars the mafic mineral does not display a similar sodium anomaly in the µXRF analyses as to the feldspars. A pyroxene and amphibole occuring together is typical for a sodium fenite (Elliot et al., 2018). This coeval existence of the two minerals could reflect the development of the fenitising fluids, where the later phases replace the first dominant fenitisation products (Hogarth & Lapointe, 1984). At Silai Patti, Pakistan the K-fenite is cut by later carbonatite dykes which have caused sodic fenitisation. In these fenites magnesio-arfvedsonite is found on the edges of aegirine-augite aggregates. This is presumed to be a direct cause of the introduction of the sodic fluids to the K-fenite (LeBas, 2008).

6.3 Categorisation of observed fenites into fenitisation grades

6.3.1 Low-grade fenite

Fenite gneiss is deemed low-grade in multiple fenite aureoles with Siilinjärvi being no exception. Pyroxene and alkaline feldspar formation during desilication is the first stage of fenitisation and visible furthest away from the carbonatite-glimmerite intrusion and closest to the basement gneiss. Relict minerals and textures are common in low-grade fenites at Siilinjärvi e.g. gneissic banding (where some relict biotite is present) and quartz that is still visible in the matrix. Sample SIKA-2018-53.1 from the eastern branch is a typical low-grade fenite. Patches of a dark mineral assemblage (aegirine-augite) has formed together with alkaline feldspar and quartz while the gneissic banding is starting to break down (I, III). Alkali-metasomatic alteration has affected the edges of the primary minerals e.g. albitisation around primary feldspar (II). The accessory minerals are unchanged from the basement gneiss with carbonate, apatite and opaques present in the low-grade fenites.

(I) Formation of aegirine augite

$3SiO_2 + NaAlSi_3O_8 + FeO, MgO, Na_2O, CaO$ (fenitising fluids) $\rightarrow 3(Ca,Na)(Fe,Mg)Si_2O_6 + Al_2O_3$

(II) Albitisation at the rims of alkali feldspars

$CaAl_2Si_2O_8 + Na_2O + Al_2O_3 \rightarrow CaAl_2Si_2O_8 + NaAlSi_3O_8$

$KAlSi_3O_8 + Na_2O \rightarrow NaAlSi_3O_8$

(III) Biotite breakdown

$K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2 \rightarrow KAlSi_3O_8 + FeO + MgO$

6.3.2 Medium-grade fenite

At this stage of fenitisation the gneissic minerals, quartz, plagiocalse and biotite, are completely consumed by the alkali minerals (IV). The assemblage consists largely of aegirine-augite and microcline/orthoclase. Perthite has started to form as well as albitised rims on the secondary feldspars (V). Chessboard albite is also present in some medium-grade fenites. Aegirine-augite is more developed and deuteric alteration in the form of uralitisation is present, displaying a later sodic fenitisation event where blue amphibole has formed around the rims of the pyroxene (Verschure & Maijer, 2005). It is proposed that a large portion of the eastern fenite branch is of medium-grade fenite e.g. sample SIKA-2018-2.1 and SIKA-2018-20.1. The fenite is mostly red to pale red in colour and the mineralogy along with the microtextures remain mostly unchanged through out. The main fenite type in the northern part of the Siilinjärvi alkali complex is considered to be a medium-grade fenite.

(IV) Formation of K-feldspar

$NaAlSi_3O_8 + K_2O \rightarrow KAlSi_3O_8$

Anorthite component released during fenitisation

$CaAl_2Si_2O_8 + K_2O \rightarrow KAlSi_3O_8 + CaO$

(V) Perthite formation

$(KAlSi_3O_8)(NaAlSi_3O_8)$ in solid solution $\rightarrow KAlSi_3O_8 + NaAlSi_3O_8$ (exsolution)

(VI) Uralitisation (aegrine-augite to richterite)

$(Ca,Na)(Fe,Mg)Si_2O_6 + Na_2O + H_2O \rightarrow Na(Na,Ca)Mg_5(Si_8O_{22})(OH)_2 + FeO$

Uralitisation (aegrine-augite to riebeckite)

$(Ca,Na)(Fe,Mg)Si_2O_6 + Na_2O + H_2O \rightarrow Na(Fe)(Si_8O_{22})(OH)_2 + MgO + CaO$

6.3.3 High-grade fenite

The high-grade fenites are concentrated around the intrusion on the western fenite branch. Replacement textures such as uralitisation and albitisation are more pronounced than in lower fenite grades. In places blue amphibole has completely replaced the aegirine-augite or formed witout the process of uralitisation (. New mineral paragenesis have formed such as blue amphibole, quartz and perthite in the center of the western fenite branch. A common form of high-grade fenite is a mantle-textured alkaline feldspar rock with less mafic minerals, indicating a K-dominant fenitic fluid. Increased amount of calcite that fills micro fractures, formed within microcline and orthocalse grains is also concentrated in high-grade fenites indicating a CO_2-rich fenitising fluid which is to be expected around a carbonatite intrusion (VIII).

The mantle-textured alkaline feldspar fenites are also considered high-grade fenites. Not only do they occur in the vicinity of the intrusion in the western branch but similar mantle textures are observed in perthites found in the amphibole-rich fenites such as sample SIKA-2018-191.1 (Fig. 30). Fenites with the mantle-textured alkaline feldspars are observed to be one of the main types of high-grade fenite.

(VII) Formation of blue amphibole (richterite)

SiO_2 + $NaAlSi_3O_8$ + Na_2O, CaO, FeO, H_2O (fenitising fluids) → $Na(Na,Ca)Mg_5(Si_8O_{22})(OH)_2$ + Al_2O_3

Formation of blue amphibole (riebeckite)

$SiO_2 + NaAlSi_3O_8 + FeO + H_2O \rightarrow Na(Fe)(Si_8O_{22})(OH)_2 + Al_2O_3$

(VIII) Formation of calcite veins

$CaO + CO_2 \rightarrow CaCO_3$

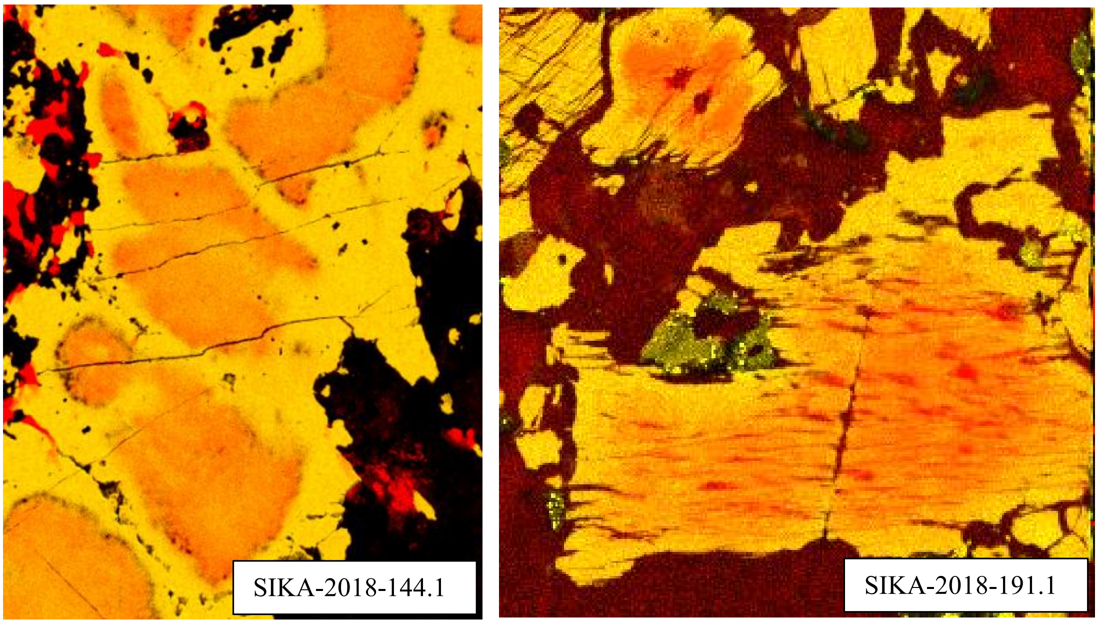


Figure 30. Comparison between mantle texture alkaline feldspar in SIKA-2018-144.1 and perthite in SIKA-2018-191.1 (both yellow). The red in the cores of the minerals signify an enrichment of Sr in the alkaline feldspars. Width of both frames are approximately 1.0 cm.

6.3.4 Contact fenite

The contact fenite is difficult to define based on the samples analysed. In the field the only confirmed contact fenite is observed to contain alkaline feldspar and carbonate, further indicating a strong K-dominant fenitisation close to the intrusion. Sample SIKA-2018-220.1 is assumed to be a contact fenite because of the phlogopite-rich part of the outcrop which is also observed in the thin section (IX). Phlogopitisation is widely reported from fenite aureoles with K-dominant fenitisation e.g. Sokli and Fen. In these alkaline complexes phlogopite is observed in high-grade fenites and in direct contact with carbonatite veins as a result of phlogopitisation of alkaline feldspars (Vartianinen & Woolley, 1976; Kresten & Morogan, 1986).

(IX) Phlogopitisation and carbonate vein formation

$$KAlSi_3O_8 + CaMg(CO_3)_2 + H_2O \rightarrow KMg_3(AlSi_3O_{10})(OH)_2 + CaCO_3$$

6.4 Comparison between western and eastern fenite branches

The most notable part of the northern Siilinjärvi alkali comlex is the branching of the fenite aureole. The principal difference between the branches is the lack of rocks belonging to the carbonatite-glimmerite series in the eastern branch. The branches are separated by an area of basement gneiss through which runs a shear zone.

The shear zone is debated to have a role in the branching of the fenite aureole. The lack of carbonatite-glimmerite rocks in the eastern branch could be because of the shear zone. The eastern branch fenite could originate from further south in the complex, namely from the area next to the Saarinen open pit. Here the carbonatite-glimmerite intrusion is in direct contact to the basement gneiss on the eastern side with virtually no fenitisation that has taken place. The lack of carbonatite-glimmerite series rocks in the eastern branch could also be explained by a deeper emplacement of the intrusion. This would explain the absence of the ore rock at the surface along with the general lower grade of fenitisation compared to the western branch.

The western branch fenites are more heterogeneous to the eastern branch. The high-grade fenitisation observed close to the intrusion varies from amphibole-rich to almost pure alkali feldspar rock, both of which are absent in the eastern branch. Quartz-rich fenite outcrops are also more scattered in the west and can be found in the center of the western aureole. This can be due to the silification conditions prevalent in the western branch (Kresten, 1988).

The fenite in the eastern branch is dominantly medium-grade along with a steady decline of fenitisation grade to the outer edges of the branch. An area in the northwest corner of the eastern branch is an exception. The fenite in this area is carbonate rich and therefore moderately weathered, similar to some high-grade fenite outcrops in the western branch. Outcrop SIKA-2018-221 also displays some variant of a mantle textured feldspar. In the western branch the mantled textured feldspar fenites are considered high-grade. The most striking similarity between this area and carbonatite-glimmerite-rich areas in the western branch is the luxuriant vegetation and somewhat micaceous sediments found in ditches and streams.

The medium-grade fenitisation is similar on both branches. They share the uralitisation and albitisation textures which are the key microscopic textures in the medium-grade fenites across the entire northern part of the Siilinjärvi alkali complex. The spatial alteration between different grades of fenites is more frequent in the western branch and the fenite is therefore more heterogeneous. In the eastern branch the bulk of the aureole is dominated by medium-grade fenites composed of different alkaline feldspar and aegirine-augite concentrations.

6.5 Desilication and silicification

The presence of quartz in fenites is common throughout fenite aureoles around the world including the Siilinjärvi alkali complex. Quartz exists mostly in fenites that are on the edges of the fenite aureole i.e. the low-grade fenites. This occurs at e.g Alnö, Fen and Iivaara alkaline complexes, where fenitisation has affected a granite gneiss (Morogan, 1994; Sindern & Kramm, 2000; Kresten & Morogan, 1986). A quartz-rich fenite is often categorised as a low- to medium-grade fenite since they are usually furthest away from the intrusion and the desilication has affected these fenites less with relict quartz still present. The desilication of the country rock is the first reaction to occur during fenitisation and is a common denominator among fenites (Le Bas, 2008).

The destination of the mobilised silica is contested. Silicification in form of quartz grains and quartz-rich veins is common around the edges of the Siilinjärvi complex. This is also the suggested destination of the silica at some areas in the Fen and Sokli complexes (Kresten & Morogan 1986 and Vartiainen & Woolley 1976). The quartz-rich fenites near the intrusion are also formed by silicification. But instead of the fluids travelling outwards to the periphery, the silica travels inwards, towards the intrusion. Silicification near the intrusion has been recorded at Alnö where calcite and silica have formed wollastonite in the contact to the carbonatite (Skelton et al., 2007). At Melteig, in the Fen complex (Norway), quartz is observed in fenites, that are classified as high-grade because of their close proximity to the intrusion (Kresten, 1988). Similar to the observations at outcrop SIKA-2018-191, SIKA-2018-193 and SIKA-2018-195 the quartz in Melteig is opalescent and contains amphibole inclusions. Speculation of the protolith can arise as well as the P-T-X conditions, which can vary. Coincidentally, the same samples from Fen, which share a similar silicification pattern as the aforementioned Siilinjärvi samples, also share the highest gains in Na-content (Kresten, 1988). This may rule out the possibility of a different protolith and favor the hypothesis of varying P-T-X conditions within the system allowing silicification near the intrusion.

6.5.1 Blue quartz

The Na-rich fenites in Siilinjärvi contain quartz with a blue hue. The amount of quartz in these fenites is abnormal since it could be classified as a main mineral. It also occurs solely in fenites with a higher than normal sodium content together with the blue amphibole, which is presumed to be richterite or riebeckite. Quartz can appear blue because of small needle-like inclusions of riebeckite in the quartz**.** Interestingly, blue quartz occurs also in the basement gneiss ca 5 km west of the Siilinjärvi alkali complex. The blue quartz grains are up to 1 cm across and are scattered over a substantial area. Their age is presumed to be Archean, since they are absent from rocks that are determined to be Proterozoic (Lukkarinen, 2008). According to Lukkarinen (2008) the presumed source of the blue quartz is the alkali metasomatism that occured during the emplacement of the Siilinjärvi alkali complex.

6.5.2 Role of the pyroxenes

Pyroxene replaces quartz during fenitisation and forms as a result of fenitising fluid phases and SiO_2 (Sinder & Kramm, 2000) This is observed in early formation of aegirine-augite at Sokli, which is in between quartz and alkaline feldspar (Vartiainen & Woolley, 1976). The clinopyroxene aegirine-augite is the main mafic mineral in Siilinjärvi fenites and occurs mostly as aggregates and veins. The aggregates can be up to a metre in diameter while the veins range from 1 cm to a metre in width. These can contain quartz grains either in the core or at the edges of the so called pyroxenites.

The importance of the vein-type pyroxenite is highlighted by Sinder & Kramm (2000). During fenitisation the removal of silica causes a loss of volume in the rock. However, taking into account the vein pyroxenites the loss of volume is decreased significantly. According to Sinder & Kramm (2000) the pyroxenite veins at Iivara are formed by the reaction of the intrusion derived fenitising fluid phase and SiO_2, which is supported by the $^{87}Sr/^{86}Sr$ isotope ratio of the Iivara pyroxenite veins. The Iivara pyroxenite veins have an $^{87}Sr/^{86}Sr$ ratio between the fenitising fluid phase and the fenite in which the pyroxenite veins occur, suggesting that the pyroxenite veins are the result of the interaction between the fenitising fluid phase and the SiO_2 released by the surrounding fenite. This means that SiO_2 is not transported out of the system during fenitisation but instead forms pyroxenite veins and aggregates, balancing out the volume loss of the fenite. The similarities between the Iivara and Siilinjärvi pyroxenite veins are abundant. They share the mineralogy of aegirine-augite with minor alkaline feldspar and quartz. The grain size of the pyrexenites is also usually larger when compered to the surrounding fenite.

6.6 Relict or metasomatic alkaline feldspar

The composition of the basement gneiss is largely homogeneous with the only variable being the amount of microcline. It can be completely absent or an accessory mineral. This causes a few issues in determining the origin of microclines and orthoclases in low- to medium-grade fenites. The alkaline feldspars formed during fenitisation replaces biotite at the onset of fenitisation. This means that primary and secondary alkaline feldspar can be present at the same time. Reports from Alnö and Fen suggest that primary microcline is more stable than the plagioclase, which is quickly turbidised and consumed (Morogan, 1994 and references therein). Albitisation can occur along the edges of primary microcline. Albitisation is widely observed in all fenite grades in this study. With fenitisation reaching medium-grade the primary microline is turbidised, or in Na-fenites, completely altered in to albite (Le Bas, 2008). In Siilinjärvi the latter does not occur. However, the existence of perthite in medium-grade fenites and their sutured margins could indicate that these alkine feldspars are secondary. This is because perthite is not observed in the Siilinjärvi migmatitic gneiss and sutured margins are a sign of recrystallization (Kresten & Morogan, 1986).

The mantle-textured feldspars are unique in a sense that they do not display albitised margins neither in µXRF analysis nor thin section. The Ti, Sr and Ba anomaly observed in the µXRF analysis are considered to be caused by the inclusions within the feldspars. The inclusions are completely absent from the rim of the feldspars, which creates the mantle texture appearance and the Ti, Sr and Ba anomaly. The anomaly is also observed in perthites in sample SIKA-2018-191.1 and in the field (Fig. 31). These inclusions could be relict mica and plagioclase from which the metasomatic feldspar has formed (Vartiainen & Woolley, 1976).

Figure 31. Mantle-textured feldspar with brown rim and creamy white core along with mantle-textured perthite with brown centre, and gray rim on outcrop SIKA-2018-188.

6.7 Challenges in defining fenitisation grade

The northern part of the Siilinjärvi alkali complex is comprised of mineralogically and texturally different fenites in a large 8 km^2-area. Identifying different fenitisation types is usually based on the distance from the intrusion and the mineralogy of the fenite. The gradual zoning of the fenitisation grade is successfully observed at e.g. the Loe Sihlman carbonatite complex in Pakistan, where the fenitisation has affected the wall rock up to 100 metres, from the intrusion (Mian & Le Bas, 1988). Difficulties arise when judging fenitisation grades in an asymmetrical complex and the subsequent asymmetry of the fenite aureole. In the studied area at Siilinjärvi the asymmetry is apparent by the branching of the complex and the lack of evidence for the carbonatite-glimmerite intrusion on the eastern branch. This means that on the eastern branch there is no reference distance between the fenite and the intrusion, which is one of the main methods in defining the fenitisation grade. Despite this, in multiple fenite aureoles around the world it has been reported that a continuous gradation of fenitisation from low-grade to contact fenite in the aureole cannot be observed (Morogan & Woolley, 1988).

The geochemical and mineralogical characteristics of two supposedly high-grade fenites can also differ within an aureole. The quartz-rich sample with blue amphibole (SIKA-2018-191.1) and the perthitic feldspar with major titanite sample (SIKA-2018-224.1) are both deemed high-grade fenites but for different reasons. In SIKA-2018-191.1 amphibole is dominant over pyroxene, implying a developed uralitic alteration connected to the later Na-rich fenitisation. In SIKA-2018-224.1 titanite is in abundance. Titanite is connected to multiple high-grade fenites such as nepheline fenites and is found together with secondary biotite and garnet in other fenite aureoles globally (Morogan & Woolley, 1988; Le Bas, 2008). However, Ti is not considered a mobile element during fenitisation, which suggests that the presence of titanite is not due to the high grade of fenitisation.

7 Conclusions

The fenite in the northern part of the Siilinjärvi alkali complex is heterogeneous due to the multiple mineralogical and textural variations. These variations are the result of a polymetasomatic fenitisation that has affected the basement migmatitic gneiss country rock. The most common type of fenite is the medium-grade alkaline feldspar and aegirine-augite fenite, which most of the eastern fenite branch are composed of. The medium-grade fenite has characteristic microtextures, which demonstrate that both K and Na have been mobile during the fenitisation. The fenitisation process, however, has been K-dominant since the bulk of the fenite consists of alkaline feldspar, aegirine-augite and iron oxides. Na-fenitisation is responsible for the albitisation and uralitisation textures formed on both primary and, secondary minerals. The low-grade fenites are found close to the unaltered basement gneiss. In these fenites relict biotite and quartz are present together with metasomatic textures and minerals caused by fenitisation such as pyroxene and the breakdown of plagioclase into alkaline feldspars. The formation of different high-grade fenites is a sign of differing P-T-X conditions during the fenitisation process. Quartz-enriched high-grade fenites show that most of the silica has stayed in the system during the formation of the fenite aureole, which is supported by pyroxene veinlets found in lower-grade fenites. Some phlogopitisation in the fenites is observed closest to the intrusion, further indicating a K-dominant fenitisation of the basement gneiss. The fenite in the northern part of the Siilinjärvi alkali complex is mostly K-dominant with influxes of Na that has formed distinct metasomatic textures and mineral assemblages.

Acknowledgements

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Swedish summary - Svensk sammanfattning

Siilinjärvi-alkalikomplexet består av en karbonatitglimmeritmalmkropp samt sidobergarterna fenit, gnejs och metadiabas. Karbonatitglimmeritintrusionen är ca 16 km lång och 900 m bred och sträcker sig i en nordsydlig riktning. Intrusionen är 2,6 Ga gammal och har intruderat det 2,8 Ga gamla bottengnejskomplexet. Intrusionen är omringad av en fenitaureol och alkalikomplexet skärs av flera metadiabasgångar med en nordvästlig-sydostlig riktning. Idag bryter Yara Suomi Oy apatitmalm i två dagbrott i Siilinjärvi.

En fenit är en metsomatisk bergart som har formats runt eller i närheten av karbonatiter och alkaliska intrusioner. Dessa intrusioner friger alkaliska fluider som förändrar sidoberget till fenit. Fenitiserande fluider består till största delen av K_2O, Na_2O, CaO, FeO, MgO, H_2O och CO_2. De förändrar sidoberget samtidigt som SiO_2 lösgörs. Flera faktorer påverkar fenitisering och slutlig bildning av fenit, de största faktorerna är de ovannämnda fenitiserande fluiderna samt tryck och temperatur. Protoliten och intrusionens sammansättning har däremot en mindre påverkan. Alla dessa faktorer gör att flera olika feniter uppstår och att fenitisering kan leda till en oändlig mängd av fenitvariationer. Fenitisering beskrivs bäst som en process där alkalierna ökar och mängden kisel minskar (desilikation), vilket även syns i fenitens mineralogi. Sidoberg som påverkats litet av fenitiserande fluider innehåller kvarts medan sidoberg som totalt förändrats till fenit innehåller alkaliska mineral såsom alkalifältspat, pyroxen och alkalisk amfibol.

Fenitens protolit i Siilinjärvi är en migmatitisk gnejs med en tonalit-trondhjemit-granodioritisk (TTG) sammansättning. Gnejsen består till största del av kvarts, plagioklas, biotit och hornblände. Kalifältspat (mikroklin) är oftast bara ett accessoriskt mineral. Karbonatit-glimmeritintrusionen består av kalcit, dolomit, flogopit, apatit och richterit. Malmmineralet apatit förekommer jämt i bergarter som hör till karbonatit-glimmeritserien i gruvan.

Kategorisering av fenit i olika fenitaureoler varierar globalt. Den mest allmänna kategoriseringen delar in fenit i Na-fenit, K-fenit och intermediär fenit. I denna avhandling tillämpas vidare kategorisering av låg-, medel- och höggradig fenit, samt kontaktfenit. Dessa termer beskriver fenitens intensitetsgrad, och distansen mellan feniten och intrusionen som de fenitiserande fluiderna härstammar från. Låggradig fenit innehåller texturer som finns i protoliten men med fenitisk mineralogi. Medelgradig fenit är dominerad av fenitiska mineral men kan även bestå av relikta mineral och texturer. I höggradig fenit har alla protolitens mineral förändrats till fenitmineral. Höggradig fenit har oftast magmatisk textur och feniten kan därför blandas med den geokemiskt liknande magmatiska bergarten syenit. En kontaktfenit sträcker sig oftast bara några meter från intrusionen. Mineralogin i kontaktfeniter reflekterar oftast intrusionens mineralogi.

Fenitiseringsprocessen för en granitisk protolit börjar med omvandling av plagioklas och nedbrytning av biotit till alkalifältspat. Kvarts får en undulerande utsläckning och förändras till pyroxen (vanligen ägirin-augit) under intensivare fenitisering. Pyroxen och alkaliamfibol formas i första hand vid korngränserna mellan alkalifältspat och kvarts. Vid vidare fenitisering förbrukas kvartsen totalt, vilket formar pyroxen och amfibol. Albit formas i kornkanterna av relikt alkalifältspat eller i nyformad alkalifältspat. I medel- och höggradig fenit kan också pertit formas i samband med sk. ‘chessboard’-albit. I höggradiga feniter är förhållandet mellan kalium (K) och natrium (Na) den största kontrollerande faktorn på mineralparagenesen. I K-dominerande feniter är huvudmineralen mikroklin, ortoklas, pyroxen och flogopit medan i Na-dominerande feniter är huvudmineralen albit, pertit och Na-amfibol.

Syftet med avhandlingen är att karakterisera och definiera olika fenittyper i norra delen av Siilinjärvi-alkalikomplexet. I detta område fördelar sig fenitaureolen i en västlig och en östlig gren. Fältkartering utfördes i området under sommaren 2018. Totalt gjordes 244 bergartsobservationer på det 8 km^2 stora karteringsområdet. De plockade bergartsproven var från fenitlokaler där fenitens mineralogi och textur representerade den lokala fenittypen. Referensprov av karteringsområdets gnejs och karbonatitglimmerit var också tagna. Till tunnslip preparerades 17 handspecimen och 11 tunnslip analyserades vidare med mikro-XRF.

Resultaten visar att fenitens färg varierar i fält från röd till blekröd, och kan i vissa fall vara nästan vit. Feniten består till största delen av röd alkalifältspat och mörkgrön klinopyroxen. Klinoyroxenen formar ställvis stora aggregat och gångar tillsammans med kvarts. Kvarts kan vara huvudmineral i låggradig och i höggradig fenit. Magnetit och andra Fe-oxider förekommer i feniter som observerats i östra fenitgrenen. Amfibolen, till skillnad från pyroxenen, är blå i fält och har observerats bara på den västra fenitgrenen i närheten av bergarter som hörs till karbonatit-glimmeritserien.

Resultaten från petrografisk tunnslipsanalys stöder mineralogiska observationer i fält. Alkalifältspaten är mikroklin eller ortoklas och klinopyroxenen är ägirin-augit. De är huvudmineralen i största delen av tunnslipen. Opaka mineral, kalcit, amfibol och kvarts är de mest förekommande accessoriska mineralen. Flera mikrotexturer är observerbara och kan förknippas med omvandling och omkristallation. Runt alkalifältspatkornen formas en koronatextur av fältspatkorn som med mikro-XRF-analys identifierats vara albit. Denna albitisering sker huvudsakligen i prov som är tagna från medelgradiga feniter. En liknande koronatextur förekommer i pyroxenerna. Pyroxenens kornkanter har ställvis omvandlats till amfibol och format en uralitiseringstextur.

Bergartsproven som är tagna inom en några hundra meters radie från intrusionen visar stora variationer i mineralogin. Mikro-XRF-analysen av en fenittyp med alkalifältspat visar att Sr, Ba och Ti utarmats vid kornkanterna. Detta har lett till att alkalifältspaten fått ett mantlat utseende. Mikro-XRF-analysen, som är kopplad till den petrografiska analysen, påvisar att alkalifältspatens kärna innehåller små mineralinklusioner. Dessa antas vara relikta mineral som förblivit i alkalifältspaten under bildandet av mineralet i fenitiseringsprocessen. Denna fenittyp klassas som en höggradig fenit.

Den amfibolrika fenittypen klassas även som en höggradig fenit. Mineralparagenesen av Na-amfibol, kvarts och pertit avviker från den tidigare nämnda fenittypen. Denna fenit har bildats till största delen av Na-dominerande fenitiserande fluider. Kvartsen har förblivit i denna fenit trots att fenitisering är en process där kiselhalten minskar.

Minskningen av kiselhalten under fenitiseringen orsakar en stor volymminskning från ursprungsbergarten gnejs. Kiseln försvinner däremot inte från systemet, utan bildar pyroxenådror och -aggregat i feniten tillsammans med fenitiserande fluider. Dessa aggregat bildas i låg- och medelgradiga feniter som tyder på att fluiderna och kiseln drivs bort från fenitiserande fluidernas ursprungskälla dvs. karbonatitglimmeritintrusionen. Tryck- och temperaturförhållandenas fluktuering under fenitiseringsprocessen kan ge upphov till kvartsrika feniter nära intrusionen. I dessa fall transporteras kiseln mot intrusionen.

Feniten i norra delen av Siilinjärvi-alkalikomplexet har bildats både genom K- och Na-fenitisering. Uralitisering och albitisering tyder på en senare Na-fenitisering efter en K-dominerad fenitiseringshändelse. Den K-dominerande fenitiseringen har bildat en medelgradig fenit som huvudsakligen består av alkalifältspat och klinopyroxenen ägirin-augit. Bildningen av flogopit i kontaktfeniter som observerats i fält stöder hypotesen av K-fenitisering. Amfibol och pertit som förekommer i vissa höggradiga feniter är ett tecken på hög variation av Na/K-förhållande i de fenitiserande fluider som förekommer i Siilinjärvi-alkalikomplexet.

Nyckelord: *Fenit, fenitisering, Siilinjärvi-alkalikomplex, alkalin metasomatism, karbonatitglimmerit, alkalifältspat, desilikation, µXRF*

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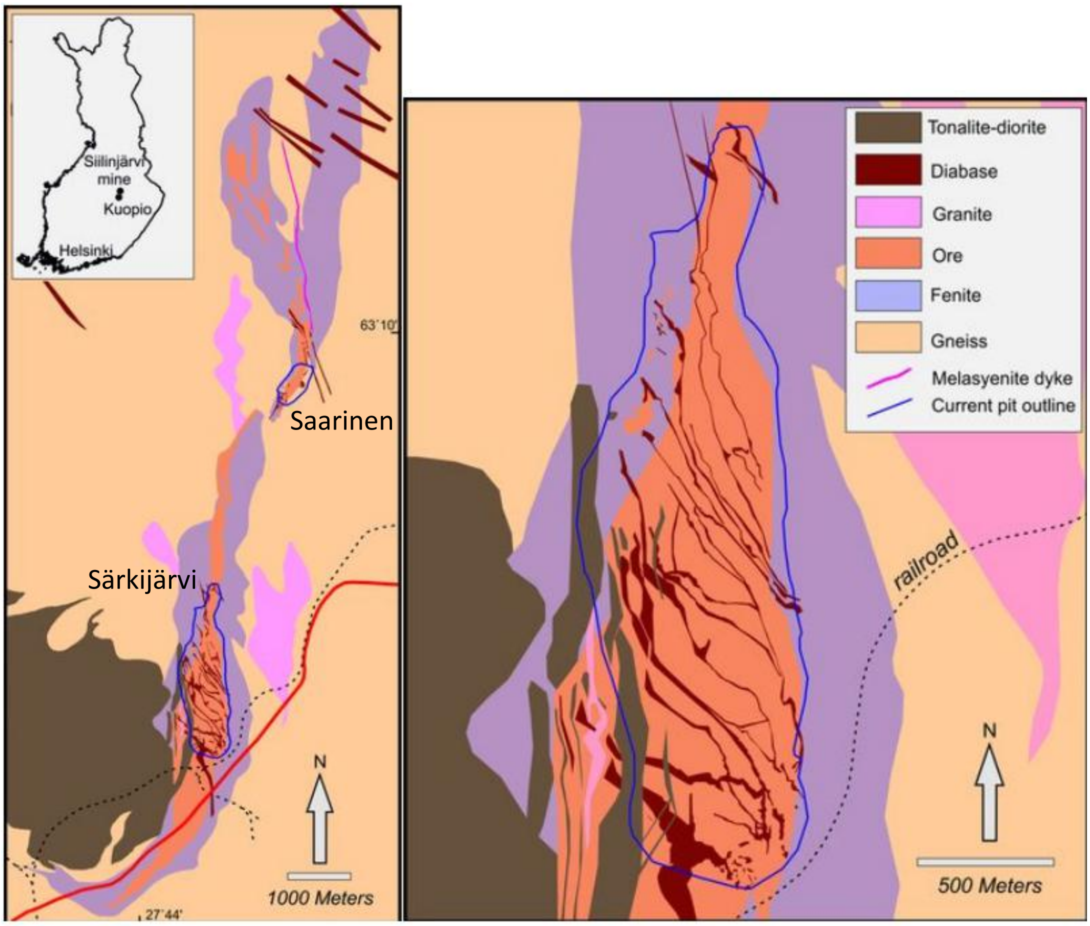
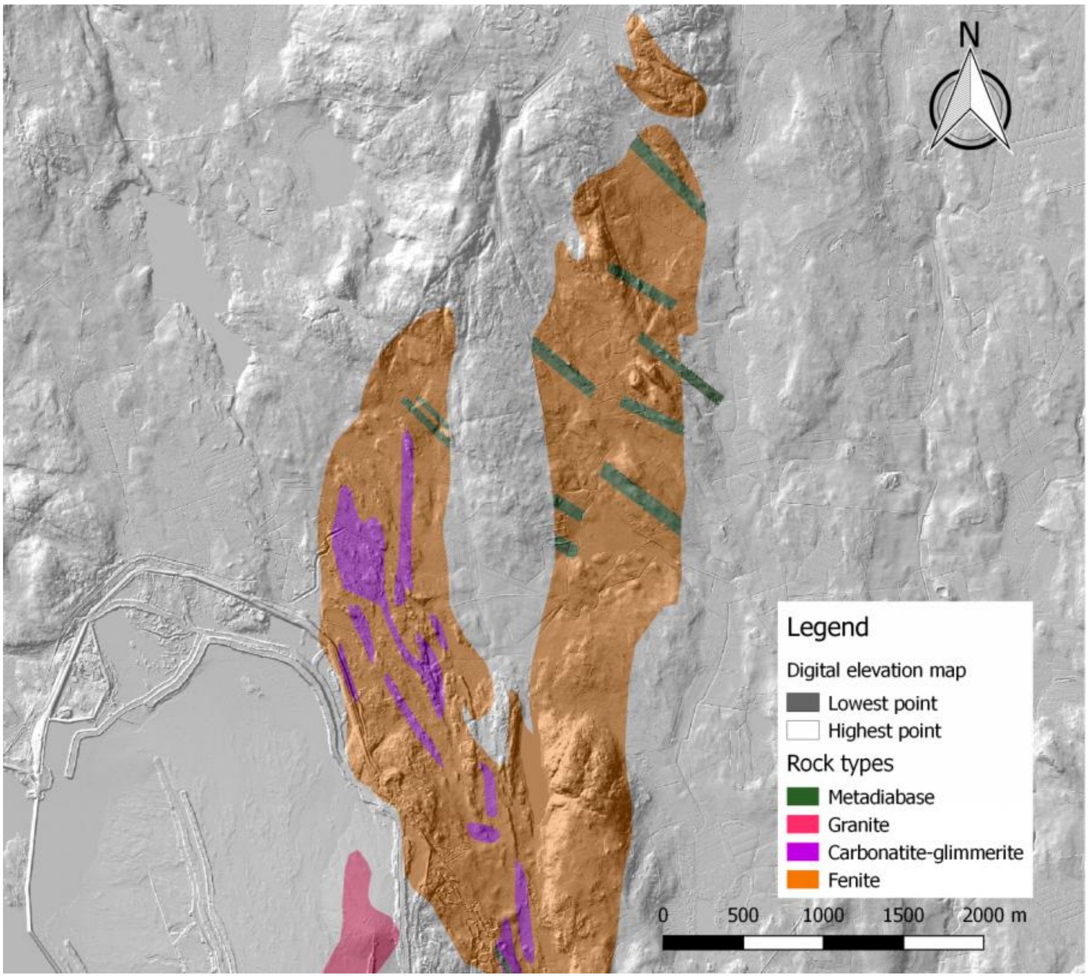
Appendices

Appendix A - Map of the Siilinjärvi alkali complex, including the mining pit outlines and a detailed bedrock map of the Särkijärvi area. Adapted from O'Brien et al. (2015).



Appendix B - Digital elevation map of the northern part of the Siilinjärvi alkali complex with the lithologies of the alkali complex.



Appendix C - The coordinates of field observations and observed rock types made during the summer of 2018. Coordinates presented in the WGS84 coordinate system.

Observation ID	Rock type	Latitude	Longitude
SIKA-2018-1	Fenite	63.19779651	27.77820711
SIKA-2018-2	Fenite	63.19822718	27.78007039
SIKA-2018-3	Metadiabase	63.19628498	27.77964439
SIKA-2018-4	Fenite	63.21004234	27.77715129

SIKA-2018-5	Fenite	63.21067361	27.77602075
SIKA-2018-6	Metadiabase	63.20975601	27.76395548
SIKA-2018-7	Gneiss	63.20189599	27.78594112
SIKA-2018-8	Gneiss	63.20176672	27.78665727
SIKA-2018-9	Fenite	63.20193935	27.78529552
SIKA-2018-10	Fenite	63.20224585	27.78436234
SIKA-2018-11	Fenite	63.20195912	27.78287716
SIKA-2018-12	Fenite	63.2014854	27.78228875
SIKA-2018-13	Fenite gneiss	63.2013058	27.78435498
SIKA-2018-14	Chlorite schist	63.2108858	27.76098394
SIKA-2018-15	Gneiss	63.2082643	27.76127507
SIKA-2018-16	Metadiabase	63.20859034	27.76202705
SIKA-2018-17	Gneiss	63.20858173	27.7624645
SIKA-2018-18	Fenite	63.20401905	27.77850531
SIKA-2018-19	Metadiabase	63.20301624	27.78564118
SIKA-2018-20	Fenite	63.21277324	27.77353104
SIKA-2018-21	Fenite	63.20972407	27.78405454
SIKA-2018-22	Fenite	63.20926666	27.78397439
SIKA-2018-23	Fenite gneiss	63.21263145	27.77179469
SIKA-2018-24	Gneiss	63.2130423	27.77068023
SIKA-2018-25	Fenite gneiss	63.21323651	27.77238897
SIKA-2018-26	Fenite	63.21304531	27.77212388
SIKA-2018-26	Fenite gneiss	63.21304531	27.77212388
SIKA-2018-27	Metadiabase	63.19991647	27.78561192
SIKA-2018-28	Metadiabase	63.19971405	27.78621051
SIKA-2018-29	Metadiabase	63.20052771	27.78494691
SIKA-2018-30	Metadiabase	63.20089358	27.78384879
SIKA-2018-31	Metadiabase	63.20102518	27.78273272

SIKA-2018-32	Fenite	63.20182641	27.78156483
SIKA-2018-33	Fenite	63.20222577	27.78144004
SIKA-2018-34	Fenite	63.20168752	27.78106348
SIKA-2018-35	Metadiabase	63.20117874	27.78152083
SIKA-2018-36	Fenite	63.20070087	27.78159293
SIKA-2018-37	Fenite	63.2132164	27.77278876
SIKA-2018-38	Gneiss	63.2133332	27.77140544
SIKA-2018-39	Gneiss	63.21400973	27.77116788
SIKA-2018-40	Gneiss	63.21351928	27.77185915
SIKA-2018-41	Fenite gneiss	63.19940117	27.75458446
SIKA-2018-42	Fenite	63.19963342	27.75194012
SIKA-2018-43	Fenite	63.20018604	27.75056064
SIKA-2018-44	Fenite	63.20076998	27.7500516
SIKA-2018-45	Fenite	63.200388	27.7486941
SIKA-2018-46	Fenite gneiss	63.20110079	27.74481685
SIKA-2018-47	Fenite gneiss	63.20087863	27.74540749
SIKA-2018-48	Fenite	63.21023703	27.77089757
SIKA-2018-49	Fenite	63.21046077	27.77135718
SIKA-2018-50	Gneiss	63.21074486	27.77148718
SIKA-2018-51	Gneiss	63.21112185	27.77144297
SIKA-2018-52	Gneiss	63.21070242	27.77274186
SIKA-2018-53	Fenite gneiss	63.21044811	27.77289363
SIKA-2018-54	Fenite	63.2102056	27.77356095
SIKA-2018-55	Fenite	63.20950908	27.77335878
SIKA-2018-56	Fenite	63.20455211	27.78335526
SIKA-2018-57	Fenite	63.20399672	27.7840909
SIKA-2018-58	Gneiss	63.20690537	27.76159461
SIKA-2018-59	Metadiabase	63.2073984	27.76357017

SIKA-2018-60	Metadiabase	63.207267	27.76282404
SIKA-2018-61	Metadiabase	63.20776853	27.76274992
SIKA-2018-62	Metadiabase	63.20679738	27.76418525
SIKA-2018-63	Metadiabase	63.20691403	27.76451903
SIKA-2018-64	Metadiabase	63.20774732	27.76513621
SIKA-2018-65	Metadiabase	63.20570201	27.76649065
SIKA-2018-66	Gneiss	63.20545404	27.76586301
SIKA-2018-67	Gneiss	63.20438404	27.76557953
SIKA-2018-68	Metadiabase	63.20671662	27.75962919
SIKA-2018-69	Metadiabase	63.20713836	27.7592724
SIKA-2018-70	Gneiss	63.20709379	27.75927907
SIKA-2018-71	Chlorite schist	63.20698287	27.758992
SIKA-2018-72	Chlorite schist	63.20681885	27.75887348
SIKA-2018-73	Chlorite schist	63.20667869	27.75878942
SIKA-2018-74	Gneiss	63.20692167	27.75881377
SIKA-2018-75	Fenite	63.20865009	27.75618698
SIKA-2018-76	Metadiabase	63.2087089	27.75363288
SIKA-2018-77	Fenite	63.20713659	27.75596435
SIKA-2018-78	Fenite	63.20712291	27.75626531
SIKA-2018-79	Fenite	63.20911402	27.77818105
SIKA-2018-80	Metadiabase	63.20896954	27.77782973
SIKA-2018-81	Metadiabase	63.20888756	27.77721055
SIKA-2018-82	Metadiabase	63.20877908	27.77713305
SIKA-2018-83	Fenite	63.20905971	27.7772899
SIKA-2018-84	Fenite	63.20877265	27.77561114
SIKA-2018-85	Fenite	63.20859857	27.77547459
SIKA-2018-86	Fenite	63.2086259	27.77751904
SIKA-2018-87	Fenite	63.20865661	27.77836116

SIKA-2018-88	Metadiabase	63.20859723	27.7797342
SIKA-2018-89	Fenite	63.20821921	27.77817295
SIKA-2018-90	Metadiabase	63.20629404	27.77759673
SIKA-2018-91	Fenite	63.20629594	27.77779264
SIKA-2018-92	Fenite	63.20629205	27.77998458
SIKA-2018-93	Fenite	63.20684783	27.78023465
SIKA-2018-94	Gneiss	63.21701928	27.78744647
SIKA-2018-95	Fenite gneiss	63.21572783	27.78365252
SIKA-2018-96	Fenite	63.21487998	27.78364222
SIKA-2018-97	Fenite	63.21476799	27.78438282
SIKA-2018-98	Gneiss	63.1952223	27.73709476
SIKA-2018-99	Gneiss	63.1953356	27.73807756
SIKA-2018-100	Gneiss	63.20218863	27.78555827
SIKA-2018-101	Gneiss	63.20217903	27.78780822
SIKA-2018-102	Fenite	63.20339033	27.78516463
SIKA-2018-103	Gneiss	63.20375907	27.78617895
SIKA-2018-104	Gneiss	63.20378361	27.78566703
SIKA-2018-105	Gneiss	63.20377536	27.78522964
SIKA-2018-106	Fenite	63.20360678	27.78496394
SIKA-2018-107	Fenite	63.20271639	27.78430405
SIKA-2018-108	Gneiss	63.20548037	27.74721203
SIKA-2018-109	Gneiss	63.20730558	27.74905888
SIKA-2018-110	Gneiss	63.20725575	27.74496953
SIKA-2018-111	Gneiss	63.20742218	27.74440393
SIKA-2018-112	Gneiss	63.20754826	27.74519768
SIKA-2018-113	Gneiss	63.20756195	27.74547349
SIKA-2018-114	Fenite	63.20541128	27.74999226
SIKA-2018-115	Fenite	63.20507211	27.75018649

SIKA-2018-116	Fenite	63.20454772	27.75116721
SIKA-2018-117	Metadiabase	63.20577168	27.74953218
SIKA-2018-118	Gneiss	63.20688003	27.7349024
SIKA-2018-119	Gneiss	63.20692134	27.73778165
SIKA-2018-120	Metadiabase	63.20694341	27.73804722
SIKA-2018-121	Metadiabase	63.2069689	27.73850096
SIKA-2018-122	Metadiabase	63.20670788	27.73903354
SIKA-2018-123	Gneiss	63.20675376	27.73914747
SIKA-2018-124	Gneiss	63.20658492	27.73900685
SIKA-2018-125	Metadiabase	63.20681225	27.73884182
SIKA-2018-126	Gneiss	63.20740722	27.73761881
SIKA-2018-127	Metadiabase	63.20734035	27.7377307
SIKA-2018-128	Gneiss	63.20751969	27.73848037
SIKA-2018-129	Metadiabase	63.20735941	27.73826668
SIKA-2018-129	Gneiss	63.20735941	27.73826668
SIKA-2018-130	Metadiabase	63.20633482	27.73934211
SIKA-2018-131	Metadiabase	63.20594565	27.73999225
SIKA-2018-132	Metadiabase	63.20578361	27.74090826
SIKA-2018-133	Gneiss	63.20585137	27.7409384
SIKA-2018-134	Gneiss	63.205502	27.74121191
SIKA-2018-135	Metadiabase	63.20578592	27.74160781
SIKA-2018-136	Metadiabase	63.20555755	27.74328535
SIKA-2018-137	Metadiabase	63.20410106	27.77089289
SIKA-2018-138	Fenite	63.20482718	27.78389142
SIKA-2018-139	Fenite	63.20528559	27.78360328
SIKA-2018-140	Fenite	63.20688725	27.78328168
SIKA-2018-141	Fenite	63.20604478	27.78114541
SIKA-2018-142	Fenite	63.20614923	27.78132462

SIKA-2018-143	Fenite	63.20314412	27.77874887
SIKA-2018-144	Fenite	63.19209868	27.74327407
SIKA-2018-145	Fenite	63.19372601	27.74396953
SIKA-2018-146	Glimmerite	63.19375635	27.74506866
SIKA-2018-147	Glimmerite	63.19164858	27.74574236
SIKA-2018-148	Metadiabase	63.19155268	27.74613096
SIKA-2018-149	Metadiabase	63.19125915	27.7465831
SIKA-2018-150	Fenite	63.18920219	27.74388865
SIKA-2018-151	Gneiss	63.20975405	27.76492231
SIKA-2018-152	Gneiss	63.20971817	27.765944
SIKA-2018-153	Gneiss	63.20992231	27.7680199
SIKA-2018-154	Gneiss	63.20935047	27.76841967
SIKA-2018-155	Gneiss	63.20854748	27.76776711
SIKA-2018-156	Gneiss	63.20874668	27.7665784
SIKA-2018-157	Fenite	63.18898776	27.74731747
SIKA-2018-158	Fenite	63.1889129	27.74825349
SIKA-2018-159	Fenite gneiss	63.19014341	27.75092839
SIKA-2018-160	Fenite gneiss	63.19014021	27.75144284
SIKA-2018-161	Glimmerite	63.19073734	27.75086108
SIKA-2018-162	Fenite gneiss	63.19066529	27.75026379
SIKA-2018-163	Fenite	63.19002592	27.74947319
SIKA-2018-164	Glimmerite	63.19070747	27.74898946
SIKA-2018-165	Glimmerite	63.19092305	27.74878699
SIKA-2018-166	Glimmerite	63.19125942	27.74933057
SIKA-2018-167	Glimmerite	63.19168946	27.7496174
SIKA-2018-168	Fenite	63.19318213	27.75119576
SIKA-2018-169	Fenite	63.19368211	27.75116322
SIKA-2018-170	Fenite	63.18079834	27.77348845

SIKA-2018-171	Fenite	63.18081139	27.77098327
SIKA-2018-172	Fenite	63.18061687	27.76986354
SIKA-2018-173	Fenite	63.18194787	27.77043499
SIKA-2018-174	Fenite	63.18302158	27.7706616
SIKA-2018-175	Fenite	63.18364653	27.77142663
SIKA-2018-176	Gneiss	63.18785039	27.74687468
SIKA-2018-177	Fenite gneiss	63.18772268	27.74960871
SIKA-2018-178	Fenite	63.18735644	27.74924387
SIKA-2018-179	Fenite	63.18672914	27.75220363
SIKA-2018-180	Fenite	63.18738072	27.7538708
SIKA-2018-181	Fenite	63.18725994	27.75438201
SIKA-2018-182	Fenite	63.18654371	27.75527997
SIKA-2018-183	Fenite	63.20355057	27.78215072
SIKA-2018-184	Glimmerite	63.18526668	27.7544096
SIKA-2018-185	Fenite	63.1956378	27.75151484
SIKA-2018-186	Glimmerite	63.19512847	27.74917324
SIKA-2018-187	Fenite	63.1956136	27.74867173
SIKA-2018-188	Fenite	63.196089	27.74823782
SIKA-2018-189	Fenite	63.19648994	27.74707196
SIKA-2018-190	Fenite gneiss	63.19668062	27.74668264
SIKA-2018-191	Fenite gneiss	63.19628015	27.74700202
SIKA-2018-192	Fenite	63.19766235	27.7473925
SIKA-2018-193	Fenite	63.19827993	27.74332793
SIKA-2018-194	Glimmerite	63.19712989	27.74374415
SIKA-2018-195	Fenite gneiss	63.19649556	27.74478874
SIKA-2018-196	Glimmerite	63.19649667	27.74498997
SIKA-2018-197	Gneiss	63.19322137	27.74068115
SIKA-2018-198	Metadiabase	63.1943256	27.74125203

SIKA-2018-199	Fenite	63.19467685	27.7426213
SIKA-2018-200	Glimmerite	63.19470214	27.74292857
SIKA-2018-201	Metadiabase	63.19523711	27.74465058
SIKA-2018-202	Fenite	63.19520358	27.74479656
SIKA-2018-203	Fenite gneiss	63.17934947	27.77764257
SIKA-2018-204	Fenite	63.17206187	27.76891897
SIKA-2018-207	Fenite	63.20864713	27.78078135
SIKA-2018-205	Fenite	63.20863728	27.7808687
SIKA-2018-206	Gneiss	63.20940646	27.78768296
SIKA-2018-207	Gneiss	63.20879083	27.78958106
SIKA-2018-208	Fenite	63.21136167	27.77492859
SIKA-2018-209	Fenite	63.1853871	27.75433321
SIKA-2018-210	Fenite	63.18533788	27.75527881
SIKA-2018-211	Fenite gneiss	63.1853023	27.75615857
SIKA-2018-212	Fenite	63.18542592	27.75623442
SIKA-2018-213	Gneiss	63.18565093	27.75670548
SIKA-2018-214	Fenite	63.18548824	27.75731719
SIKA-2018-215	Fenite gneiss	63.18453072	27.75494339
SIKA-2018-216	Fenite	63.18456709	27.75597436
SIKA-2018-217	Fenite	63.18396473	27.75663186
SIKA-2018-218	Glimmerite	63.18397366	27.75606865
SIKA-2018-219	Gneiss	63.18437712	27.75677249
SIKA-2018-219	Fenite	63.18437712	27.75677249
SIKA-2018-220	Fenite gneiss	63.18473346	27.75916674
SIKA-2018-221	Fenite	63.20985659	27.77148983
SIKA-2018-222	Fenite	63.21202866	27.7738135
SIKA-2018-223	Glimmerite	63.18317028	27.75661904
SIKA-2018-224	Fenite gneiss	63.18284432	27.75708713

SIKA-2018-225	Gneiss	63.18892411	27.75685307
SIKA-2018-226	Metadiabase	63.17989136	27.75789659
SIKA-2018-227	Fenite gneiss	63.18030177	27.762072
SIKA-2018-228	Gneiss	63.18106462	27.76236267
SIKA-2018-229	Gneiss	63.18147162	27.76189248
SIKA-2018-230	Gneiss	63.18176457	27.76183634
SIKA-2018-231	Gneiss	63.1821788	27.75979895
SIKA-2018-232	Fenite	63.2039653	27.78146726
SIKA-2018-233	Fenite	63.18521348	27.76377455
SIKA-2018-234	Gneiss	63.18499035	27.76267446
SIKA-2018-235	Chlorite schist	63.18518647	27.76254573
SIKA-2018-236	Gneiss	63.18529227	27.7614813
SIKA-2018-237	Fenite	63.18507697	27.76035996
SIKA-2018-238	Fenite/Fenite gneiss	63.18497246	27.7604688
SIKA-2018-239	Fenite gneiss	63.18440035	27.7597995
SIKA-2018-240	Fenite	63.18472183	27.76360774
SIKA-2018-241	Fenite	63.1806716	27.75518062
SIKA-2018-242	Gneiss	63.19442132	27.76434947
SIKA-2018-243	Metadiabase	63.20008799	27.75580702
SIKA-2018-243	Gneiss	63.20008799	27.75580702
SIKA-2018-244	Fenite	63.2019562	27.75250619

Appendix D - Micro-XRF analysis map of SIKA-2018-177.1 with K and Ba compered to K and Ti, which displays that Ba and Ti are similarly distributed. The black areas within the yellow areas (K) are areas enriched in Ba and Ti. The width of each frame is 5.5 cm.